Overview and Status of the National Ignition Campaign on the NIF

Presentation to
Ignition Science Workshop
May 23-24, 2012

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UCRL-PRES-558211

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

National Ignition Campaign

NNSA
National Nuclear Security Administration

GENERAL ATOMICS

UR LLE

Lawrence Livermore National Laboratory

Los Alamos NATIONAL LABORATORY

Sandia National Laboratories

MIT

AWE

cea

NSTec

BERKELEY LAB

Duke UNIVERSITY

The National Ignition Facility

The capabilities of the laser, targets, diagnostics, and experimental platforms are now in place for the push to ignition

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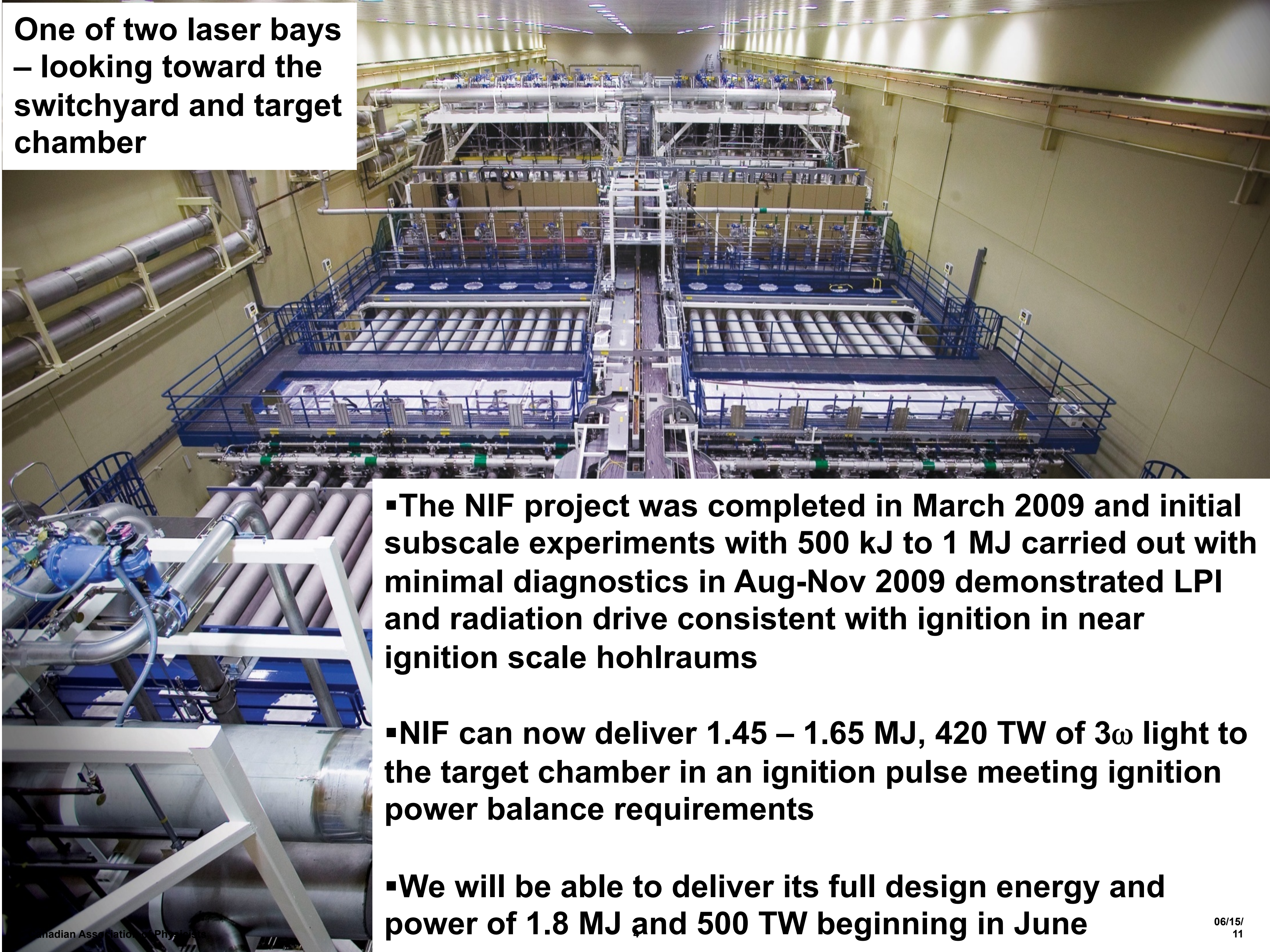


One of two laser bays – looking toward the switchyard and target chamber

- The NIF project was completed in March 2009 and initial subscale experiments with 500 kJ to 1 MJ carried out with minimal diagnostics in Aug-Nov 2009 demonstrated LPI and radiation drive consistent with ignition in near ignition scale hohlraums

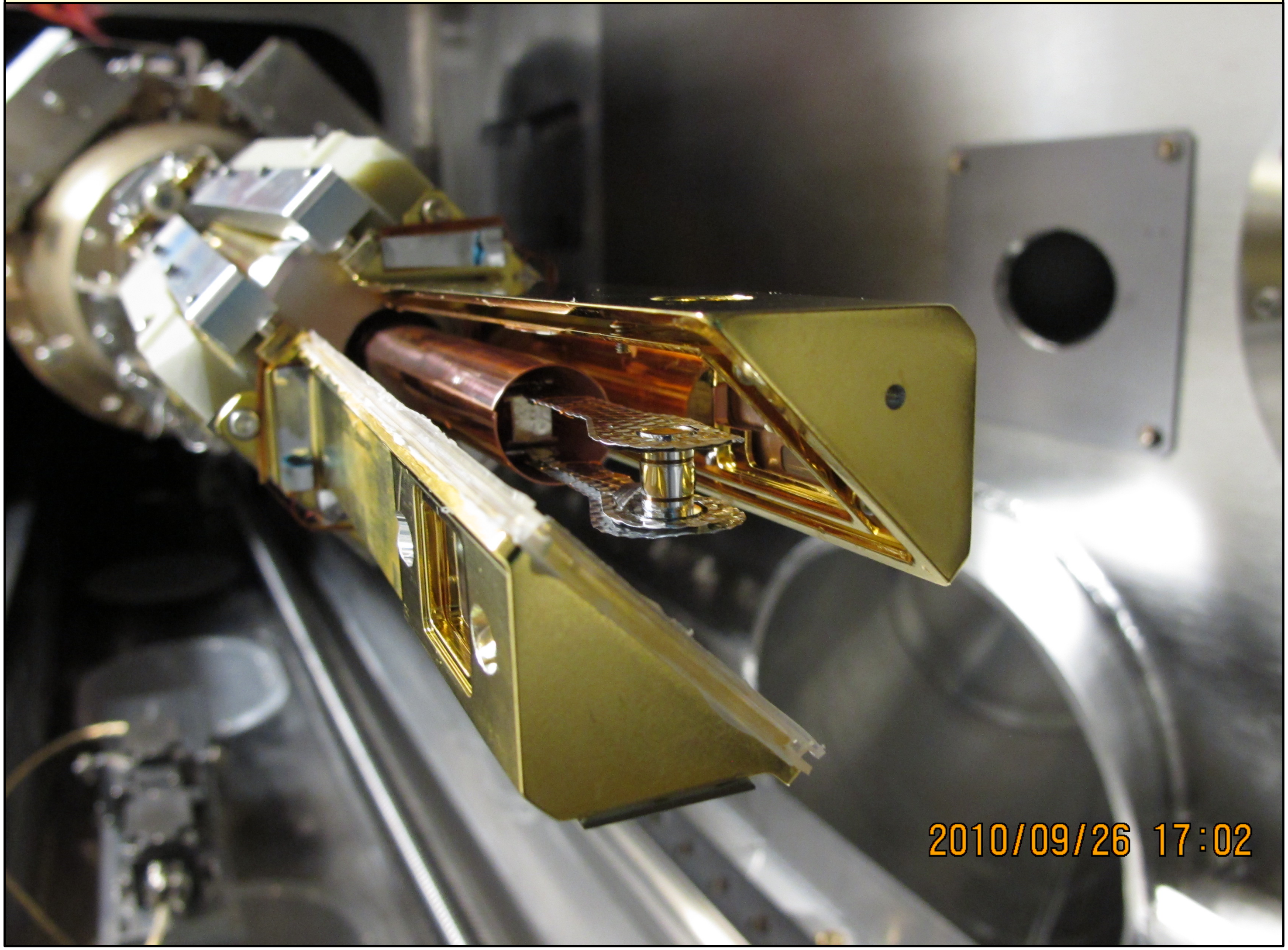
- NIF can now deliver 1.45 – 1.65 MJ, 420 TW of 3ω light to the target chamber in an ignition pulse meeting ignition power balance requirements

- We will be able to deliver its full design energy and power of 1.8 MJ and 500 TW beginning in June

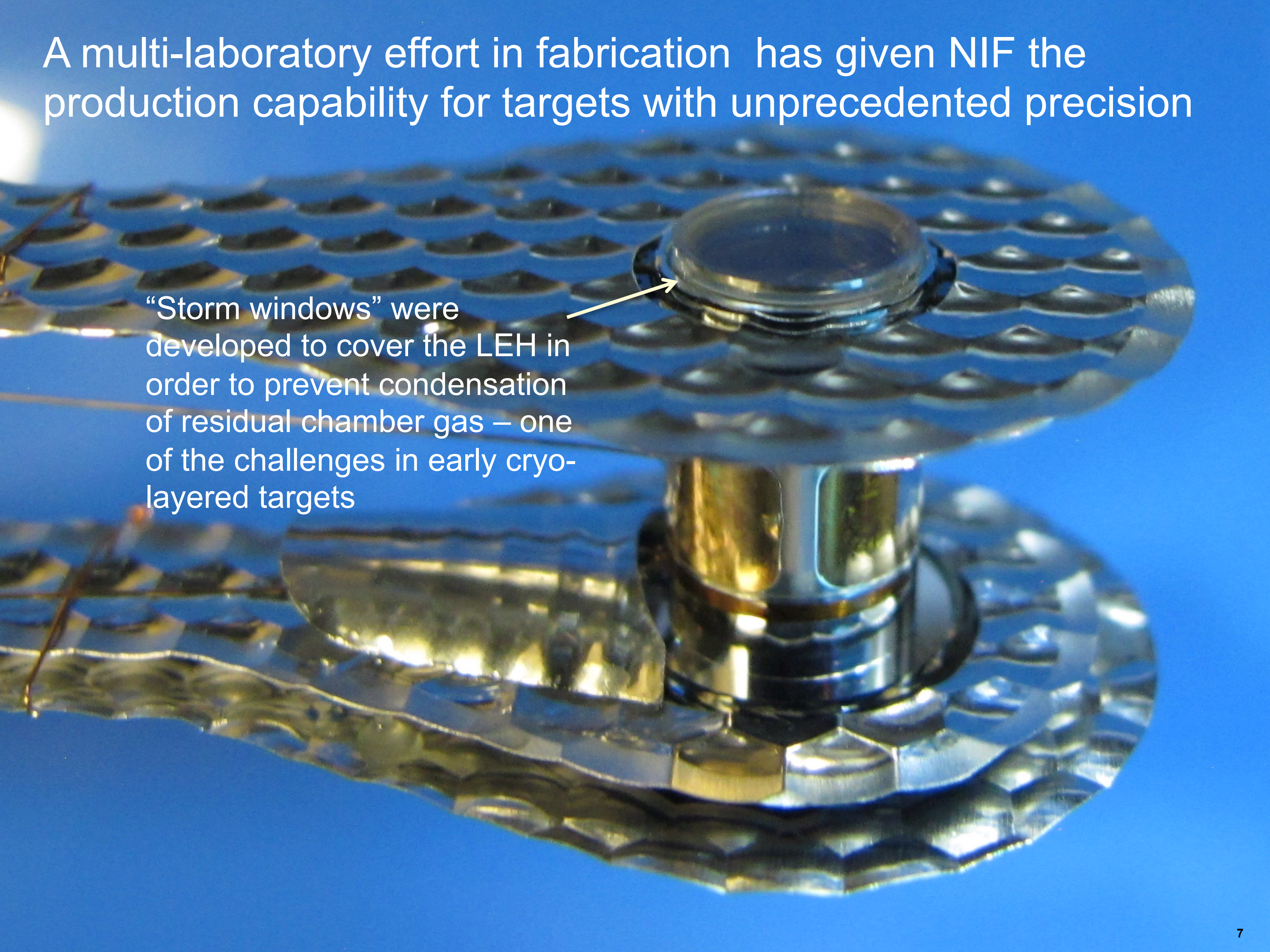
December 2009 to September 2010 was devoted to installing major infrastructure and nuclear diagnostics: The CryoTarpos supports formation of cryogenic fuel layers outside the chamber prior to insertion into target chamber center at shot time

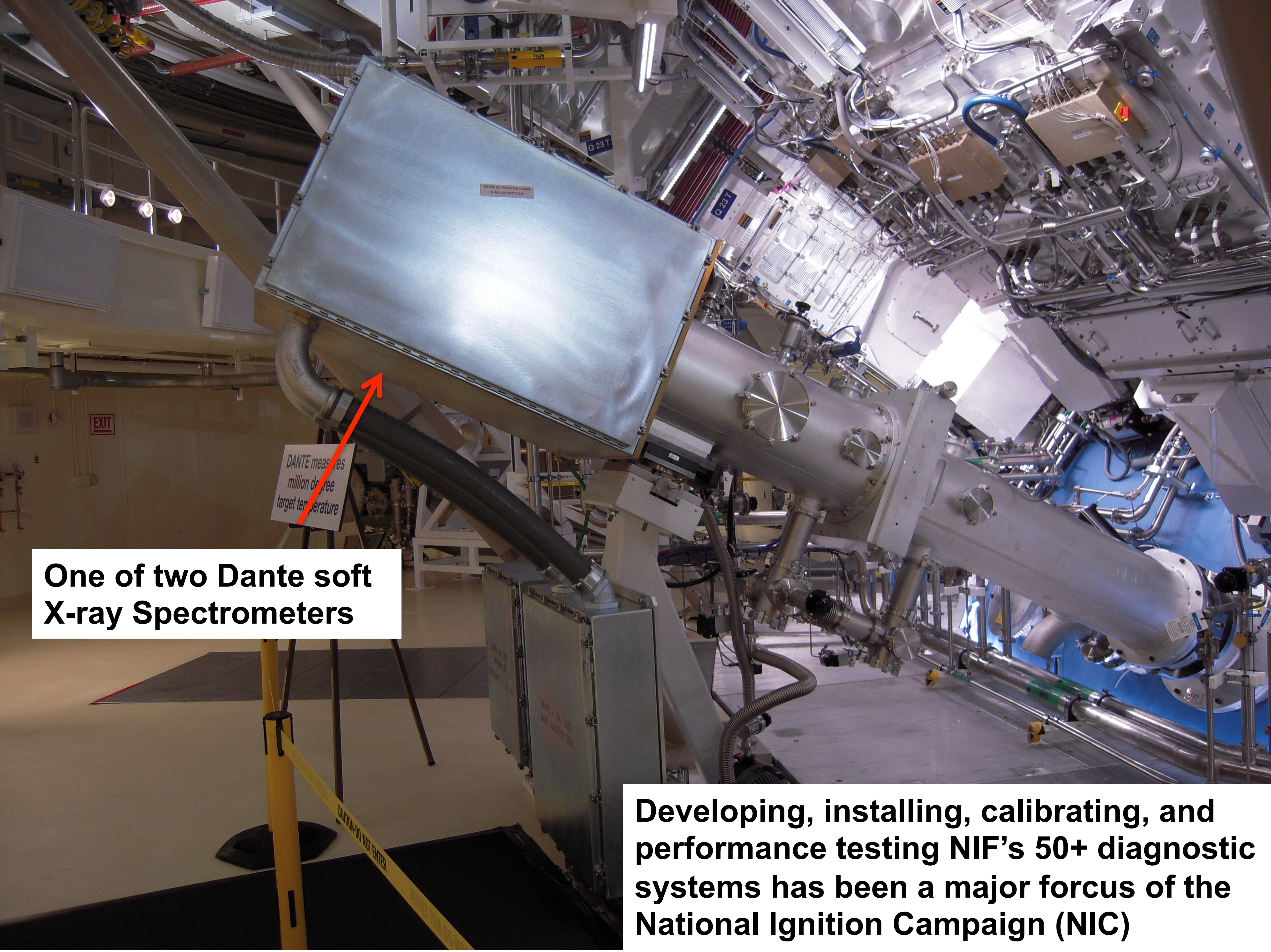
THD fuel layers are formed with the target mounted in a dedicated cryogenic target positioner thermally isolated by a removable shroud

27850001 target in layering shroud



A multi-laboratory effort in fabrication has given NIF the production capability for targets with unprecedented precision





One of two Dante soft X-ray Spectrometers

Developing, installing, calibrating, and performance testing NIF's 50+ diagnostic systems has been a major forcus of the National Ignition Campaign (NIC)

There are multiple time scales for the use and evolution of numerical models within the NIC

Models

- Equations
- Algorithms
- Databases
- Computers

Preshot using ab initio model prior to initial data

- Specifications,
- Playbooks
- Scenario Development
- Campaign Strategy – Sudoku

Near Term – Shot-to-shot during the Campaign

Data Modified Models

- Data informed playbooks,
- Preshot – Expected performance informed by data
- Scenario development with models modified to match existing data
- Specifications modified by data

Longer Term – Improvements to models

- DCA for hohlraum and non-local thermal conduction now part of standard model
- Improvements to EOS, and NLTE for ablator now under development

Updates to point design based on new data

- Revisions to CH point design
- Updated ignition designs using alternate ablators (Be,HDC, B_4C, Al) and modified hohlraum geometry

Postshot using as-shot conditions

Experiments Data

Summary of Ignition Campaign Status

- **We are one year into the campaign to carry out precision optimization of ignition scale implosions**

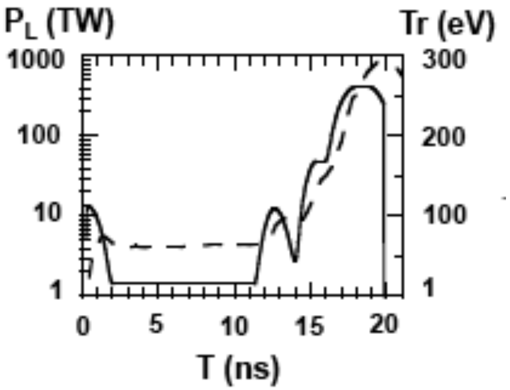
- **We have achieved hohlraum temperatures in excess of the 300 eV ignition goal with hot spot symmetry and shock timing near ignition specs**

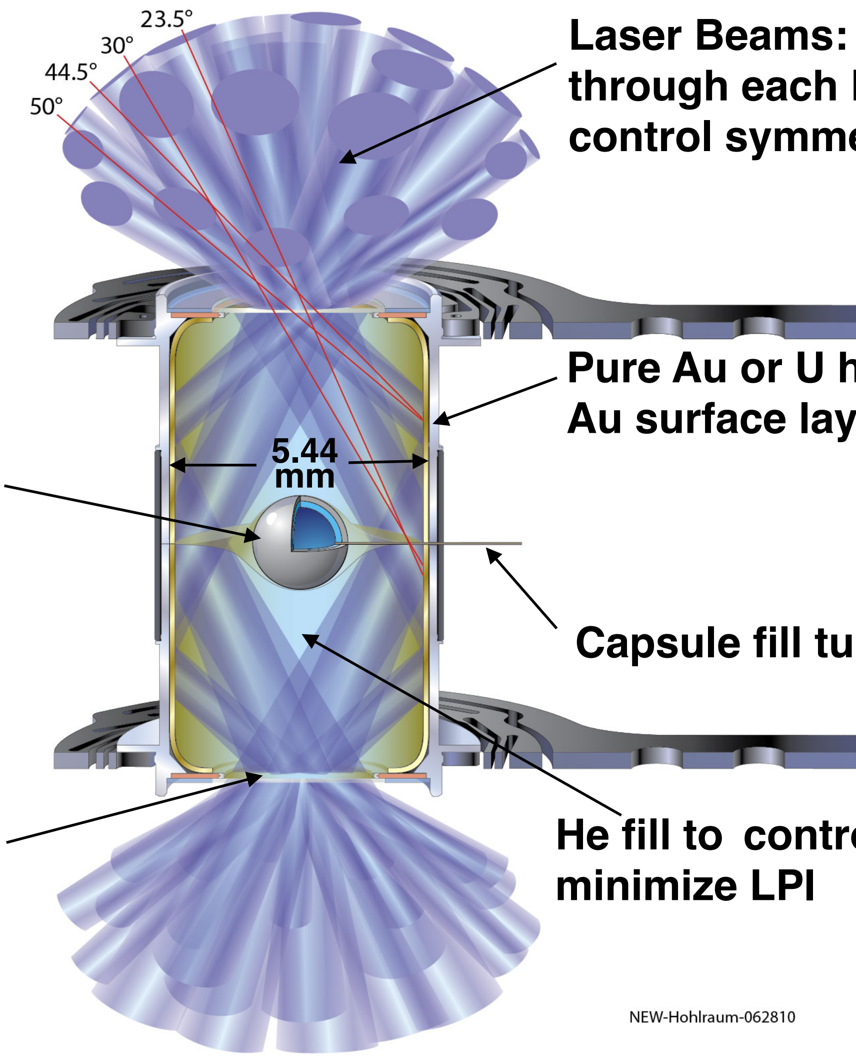
- **Slower rise to peak power and longer "no-coast" pulses result in lower hot spot adiabat and main fuel ρr at about 85% of the ignition goal**

- **Nuclear data indicates that long wavelength variation in the main fuel density may be contributing to performance degradation**

- **Mix performance boundary with more mass remaining than the point design will require thicker shells (+20-30%) to reach ignition velocity without mix**

Ignition Target designs have a number of general features





Laser Beams: 24 quads through each LEH arranged control symmetry

Pure Au or U hohlraum with Au surface layer

Capsule with low-z ablator (CH, Be, or HDC*) and cryo fuel layer

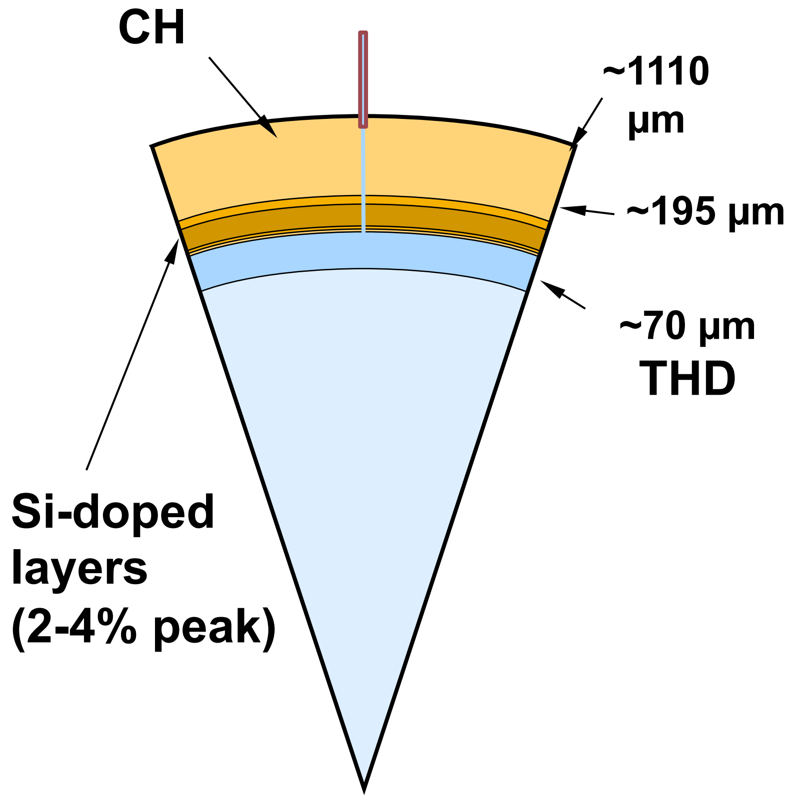
Capsule fill tube ~10 µm

Laser Entrance Hole sized to balance LPI and radiative losses – 56–60% of LEH diameter

He fill to control symmetry and minimize LPI

***High Density Carbon**

The initial ignition campaign is using a CH capsule



- Amorphous material with no crystal structure issues
- Large data base from the Nova and Omega (LLE) lasers
- Reduced Facility impact relative to Be
- All of the diagnostics and infrastructure needed for optimizing ignition implosions are essentially independent of capsule ablator

- Silicon doped layers reduce X-ray preheat at ablator-DT interface to make favorable Atwood number during acceleration to control mix
- Ablator thickness is adjusted to vary sensitivity to mix of fuel and ablator resulting from ablation front instability growth

To achieve ignition, the NIC must generate the data needed to optimize the principal characteristics of an ICF implosion

>200 actionable target design parameters

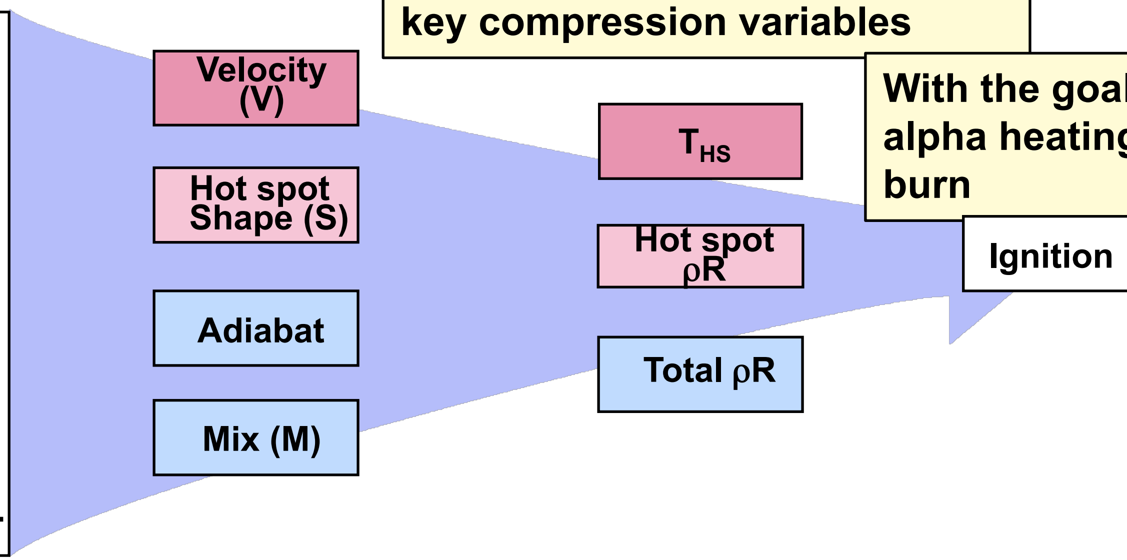
The NIC aggregates the impact of hundreds of actionable input variables into their impact on four key implosion input variables

And assess performance by measuring improvements to the key compression variables

With the goal of alpha heating and burn

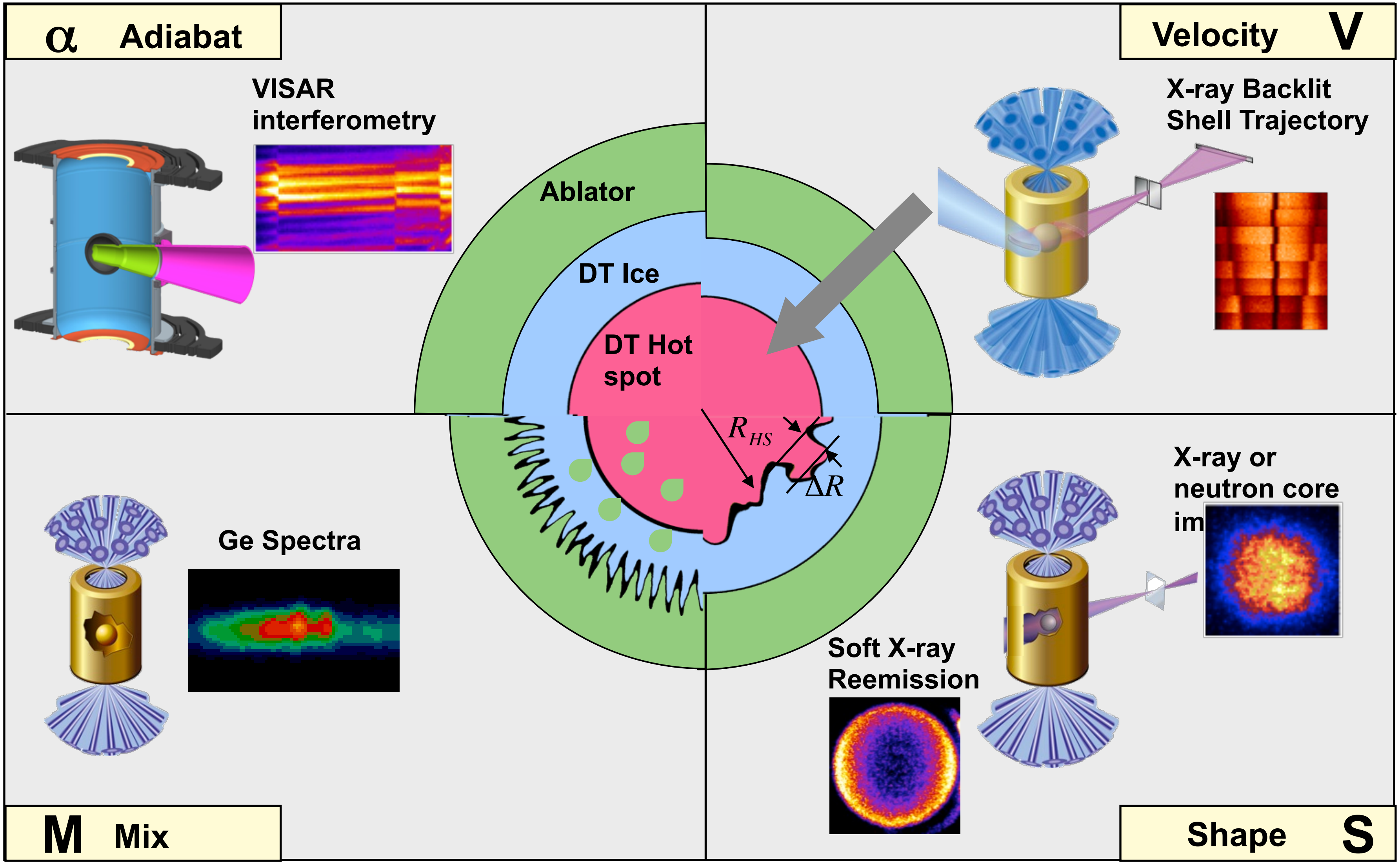
1D quantities,
e.g:
Peak Laser Power
Foot Laser Power
Shock timing

3D quantities,
e.g:
Ice Perturbations
Capsule Roughness
Intrinsic Asymmetry
Laser Power Balance …



- The key variables for ICF have been known for decades
- Since NIF was first proposed, we have worked to better quantify the specifications for ignition at the megajoule scale

From September 2010 to April 2011, the NIC focused on validating a series of experimental platforms to optimize the capsule shape, adiabat, velocity, and mix



The National Ignition Campaign (NIC) is designed to generate the data needed for an optimal implosion in the most efficient sequence of experiments

NIC

Observables		Picket cone fraction	Foot I power, CF	Pulse timing, 4^{th} slope	Peak cone fraction, $\delta\lambda_2$	Hohlraum length, LEH, Pointing	$\delta\lambda_3$	Capsule ID, Au vs. U, Peak power	Ablator thickness	Capsule dopant %	Ice thickness	Platform
Adiabat	Picket P2											Reemit
	Shock velocity/P2											Keyhole, THD/DT, CompR, ConAW
	Shock timing/dsr/ρr											
Shape	Peak P2											Symmetry capsule or THD/DT and CompR
	Peak P4											
	Peak m4											
Velocity	Implosion velocity											ConA, THDConA
Fuel Mix	Residual mass											
	M-band											Any implosion
Hot spot Mix	Growth factor											Mixcap
	Ge/Cu emission, YoC											THD

Experimental Control Parameters

We began precision optimization experiments in May 2011 and completed the first pass through all key variables in April 2012 with the first mix campaign

Observables		Platform
Adiabat	Picket P2	Reemit
	Shock velocity/P2	Keyhole, THD/DT, CR, ConAWide
	Shock timing/dsr/ ρr	
Shape	Peak P2	Symmetry capsule or THD/ DT and CR
	Peak P4	
	Peak m4	
Velocity	Implosion Velocity	ConA, THDConA
Fuel Mix	Residual mass	
	M-band	Any implosion
Hotspot	Growth factor	Mixcap

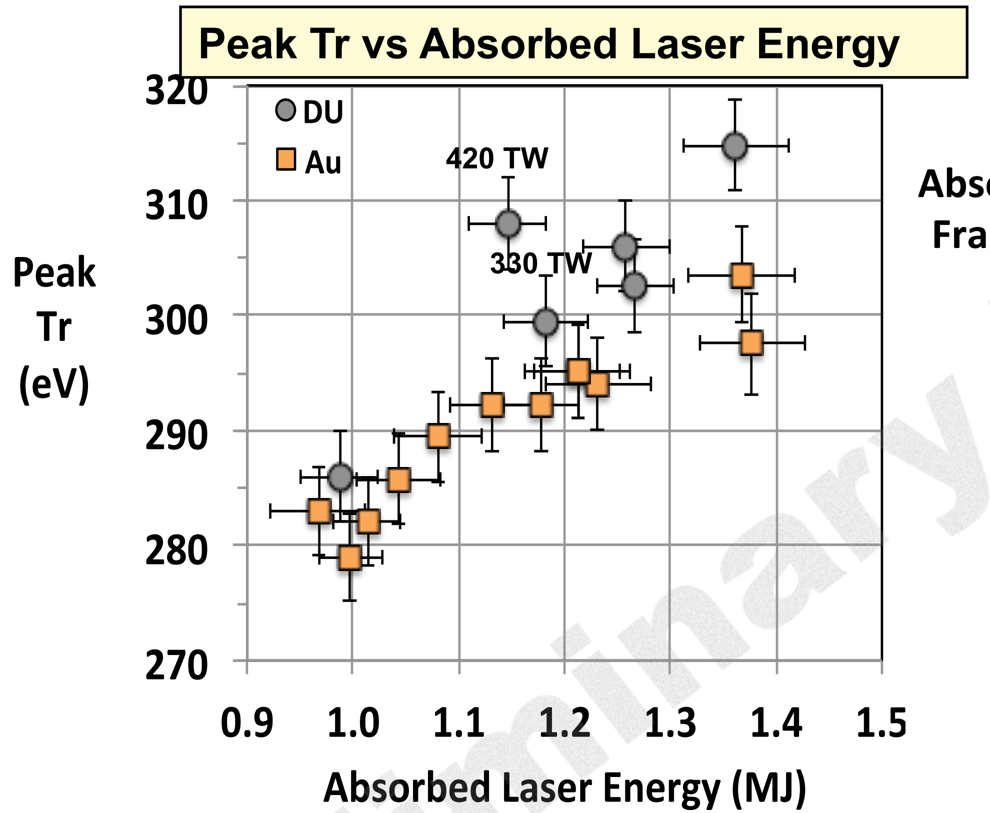
May 2011 – first precision shock timing experiments

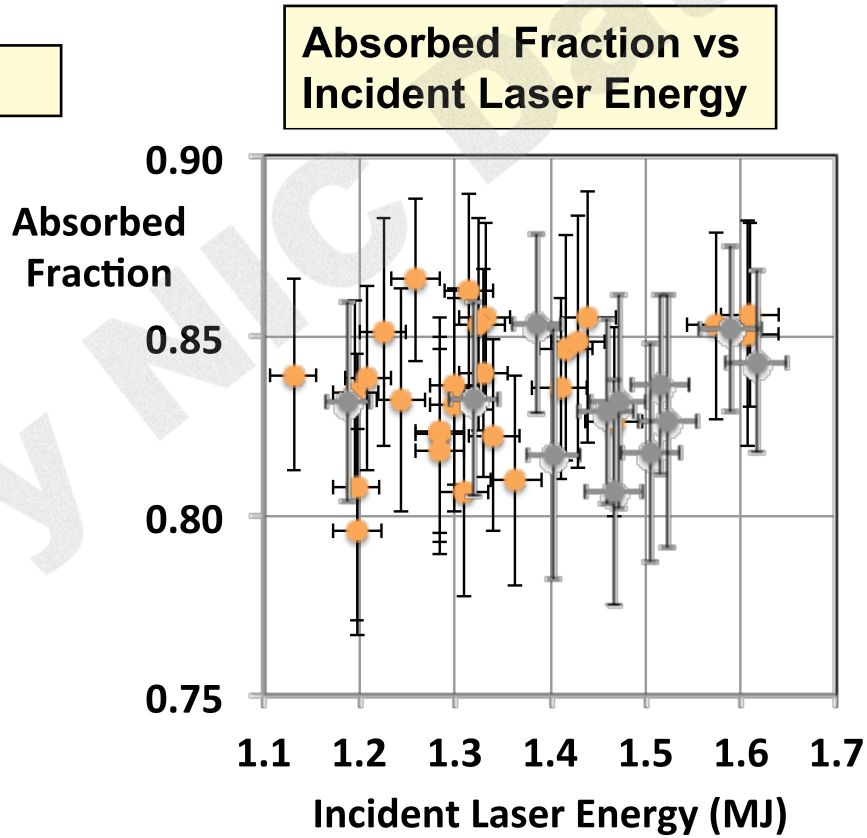
March/April 2012– first iteration on mix optimization

- The optimal sequencing was studied extensively prior to the start of experiments in the Red Team / Blue Team study
- That sequencing has been largely validated in experiments although a few new experimental platforms have been added to those originally envisioned and others may be needed to achieve ignition

We have achieved the ignition goal of Tr > 300 eV with coupling of 83±2% nearly independent of laser energy up to 1.6 MJ

9.43 mm by 5.75 mm Hohlraum, 3.1 mm LEH

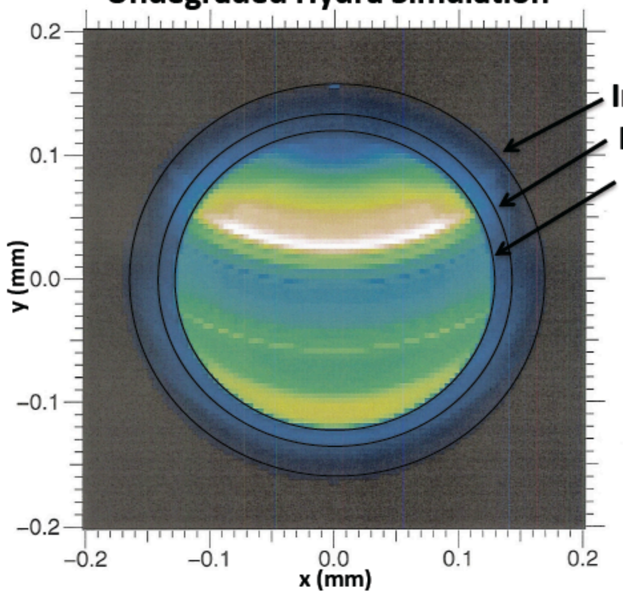




- 17% LPI losses are about twice what was anticipated prior to first experiments
- Increased loss is consistent with improved understanding of the plasma conditions resulting from the implementation of the DCA NLTE atomic physics model and non-local electron transport which results in increased importance of multi-quad overlap effects on LPI

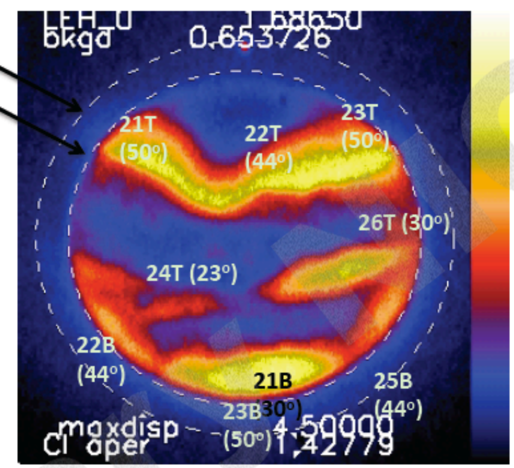
Standard calculations overestimate laser entrance hole closure by about 20%

Undegraded Hydra Simulation



Initial
Data
Sim

SXI Lower Hard Channel



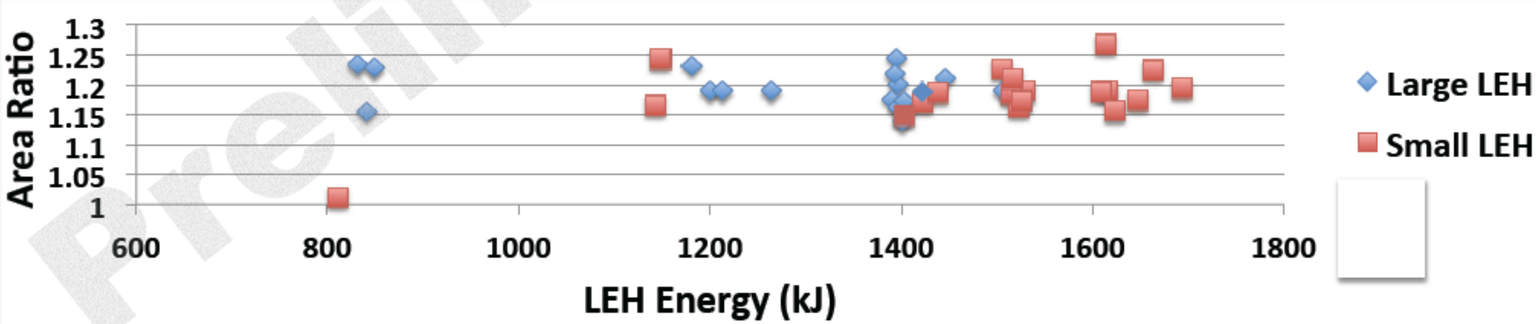
N120126, DT, Slow rise (3 ns)
Au hohlraum, Large (3.375 mm) LEH
Laser $Energy_{LEH}$ = 1393 kJ

D_{data} = 2.86 mm

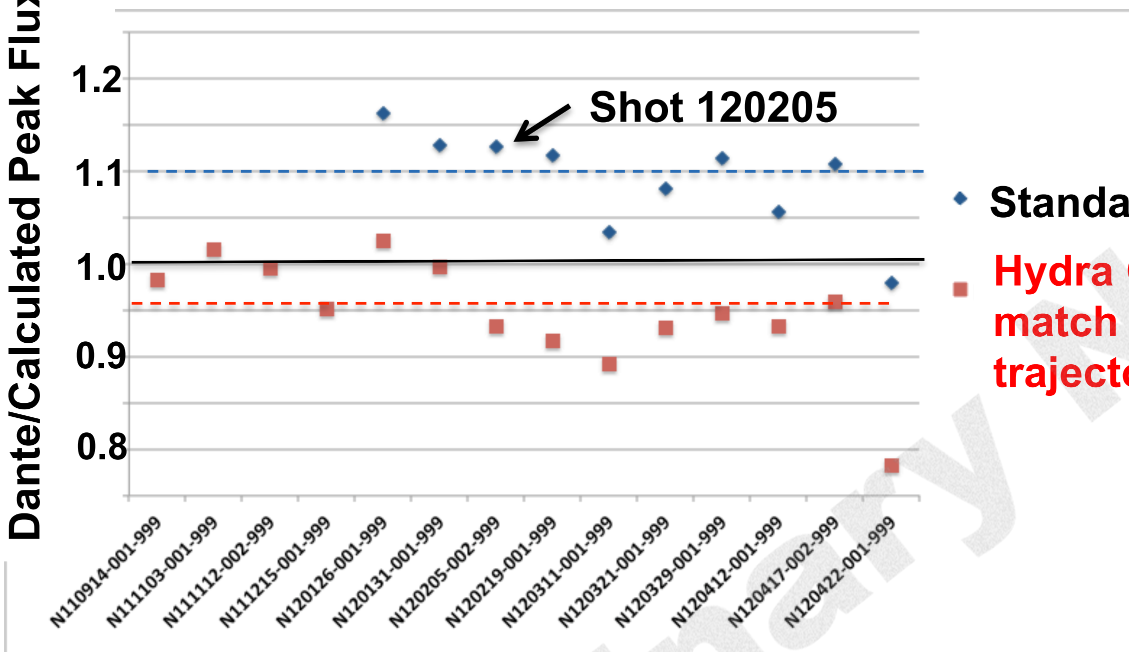
D_{sim} = 2.59 mm

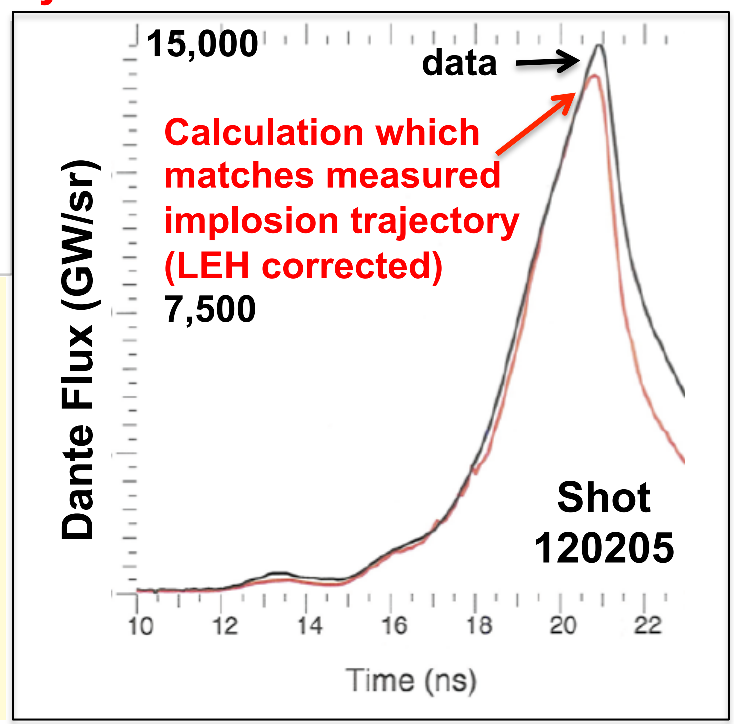
Area Ratio = 1.22

- **Recent zoning studies indicate that much of this discrepancy could be numerical**
- **Heating of the blowoff plasma by various plasma processes not included currently could help keep LEH open**



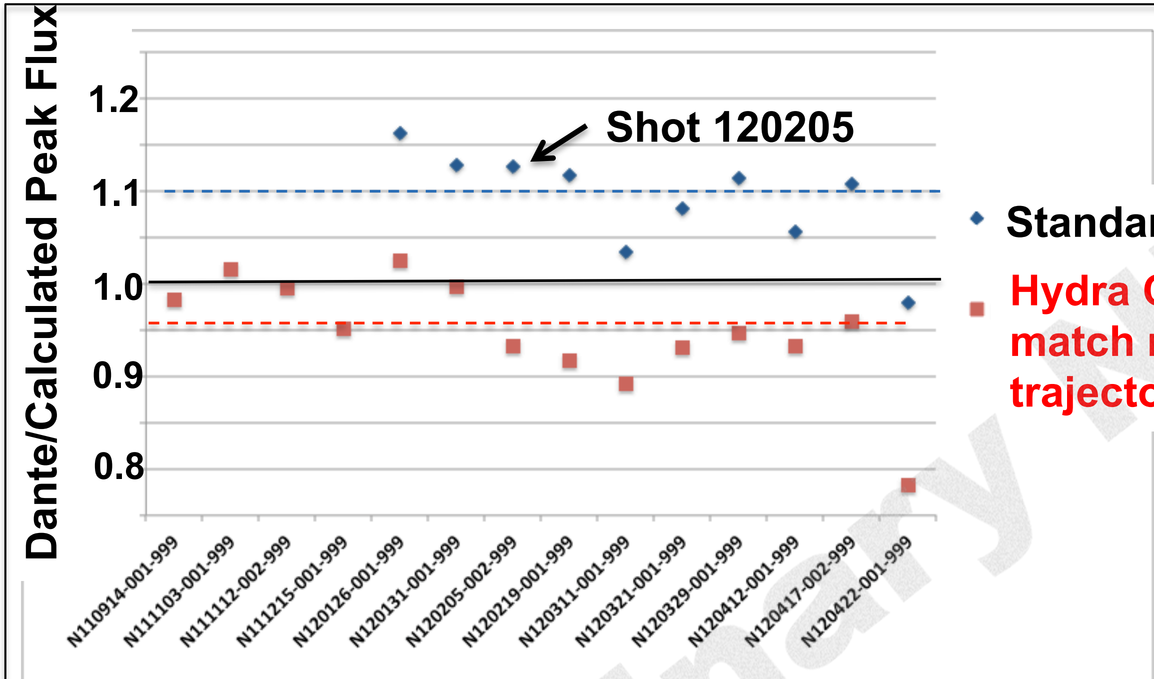
When corrected for laser entrance hole size, calculations with the flux versus time needed to match implosion trajectories, match the Dante peak flux to about 4%



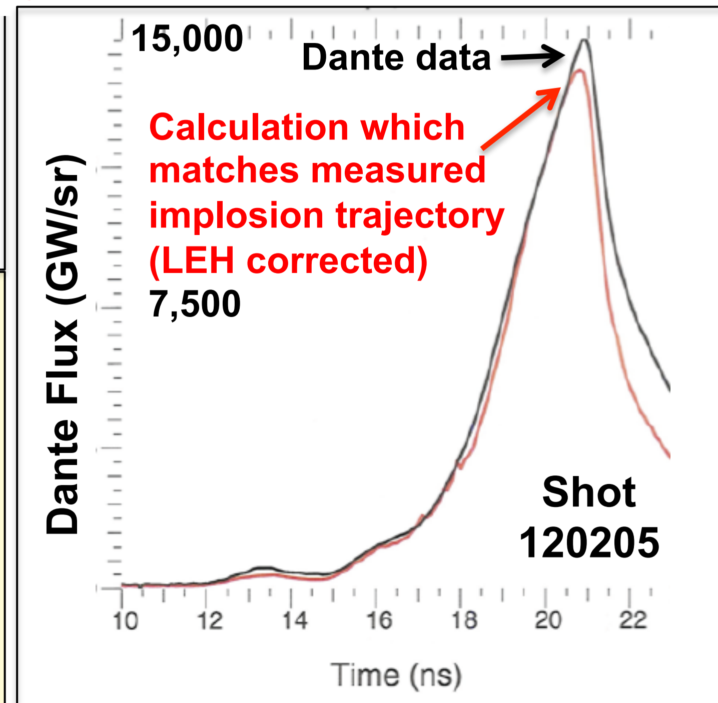


- Standard calculations overestimate the measured Dante flux by about 8% on average
  — much of this difference may be explained by numerical zoning effects in calculations
- Observed shell trajectories are consistent with about 4% less flux than observed on average
  — NLTE effects in the ablator are predicted but currently estimated to be small

Measured fluxes corrected for the observed LEH closure provide the best estimate when comparing data to calculations of the hohlraum drive and capsule response

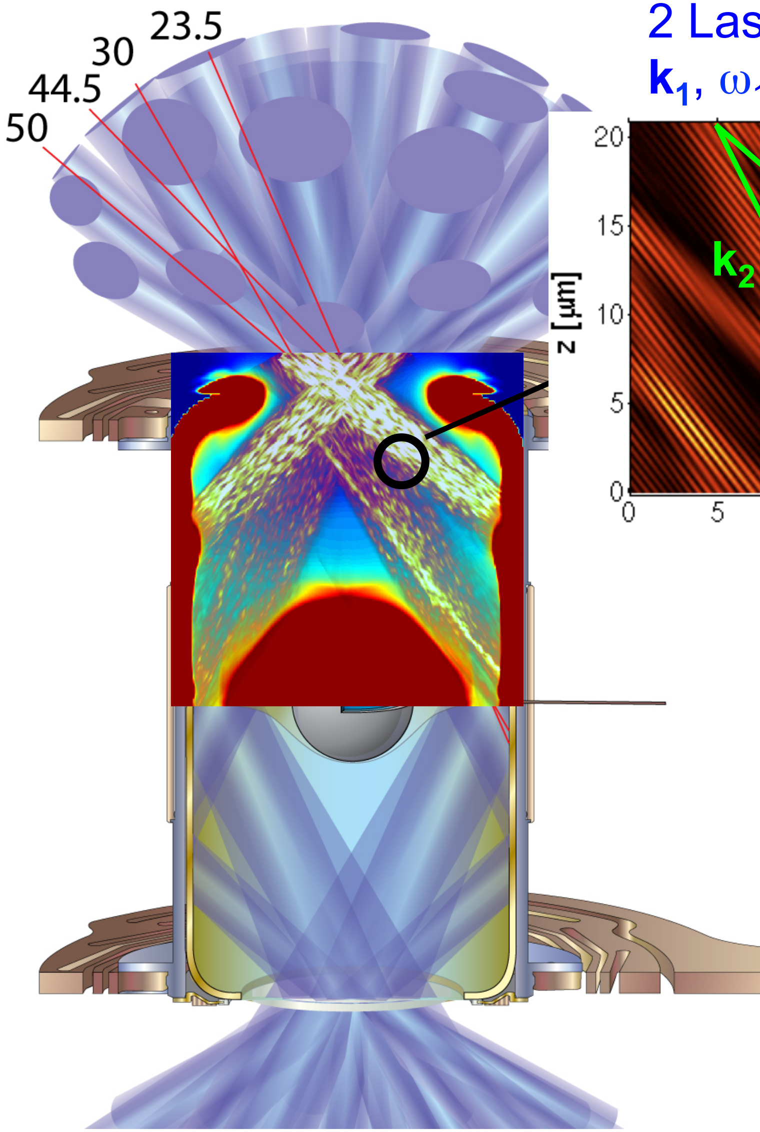


- Standard Hydra Calculation
- Hydra Calculation modified to match measured implosion trajectory



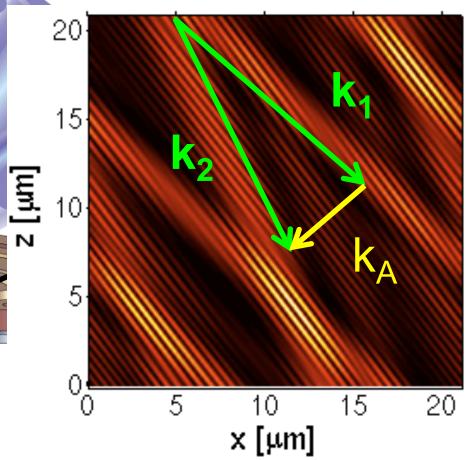
- Measured Dante fluxes are ~8% lower on average than standard Hydra calculations
  — much of this difference may be explained by numerical zoning effects in calculations
- Observed shell trajectories are responding as if the flux were about 4% less than Dante on average
  — NLTE effects in the ablator are predicted but currently estimated to be small

Crossed laser beams in the hohlraum plasmas produce intensity modulations that drive density modulations

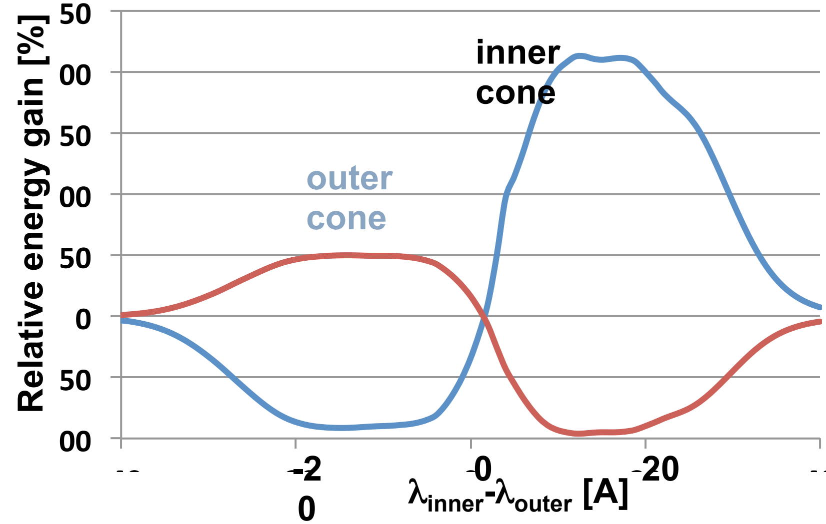


2 Lasers

$\mathbf{k}_1, \omega_1, \mathbf{k}_2, \omega_2$



$$Q \sim [(\omega_1 - \omega_2) - k_A(C_S - V) + i\nu]^{-2}$$

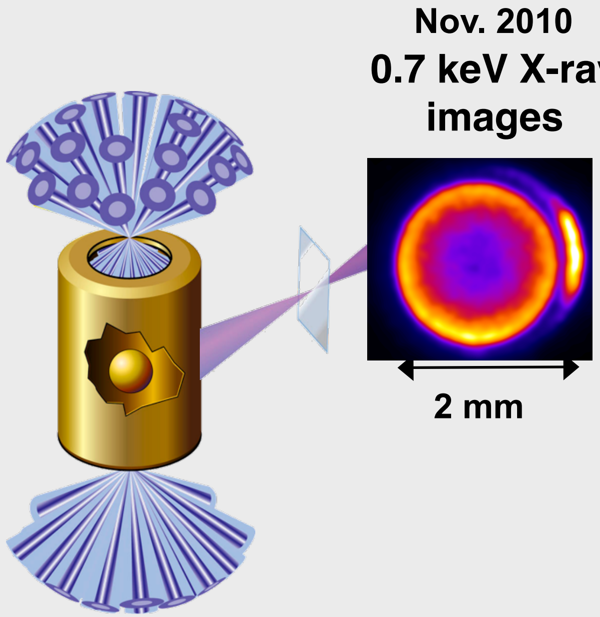


- Density modulation (grating) produced in the plasma allows energy to be transferred between beams
- Adjusting the wavelength shift between beams allows us to control energy transfer between cones
- This process can work in both directions (into and out of the hohlraum).

Reemit Target sets the cone power ratio for the first 2 ns to ensure symmetric foot drive

Experimental Geometry

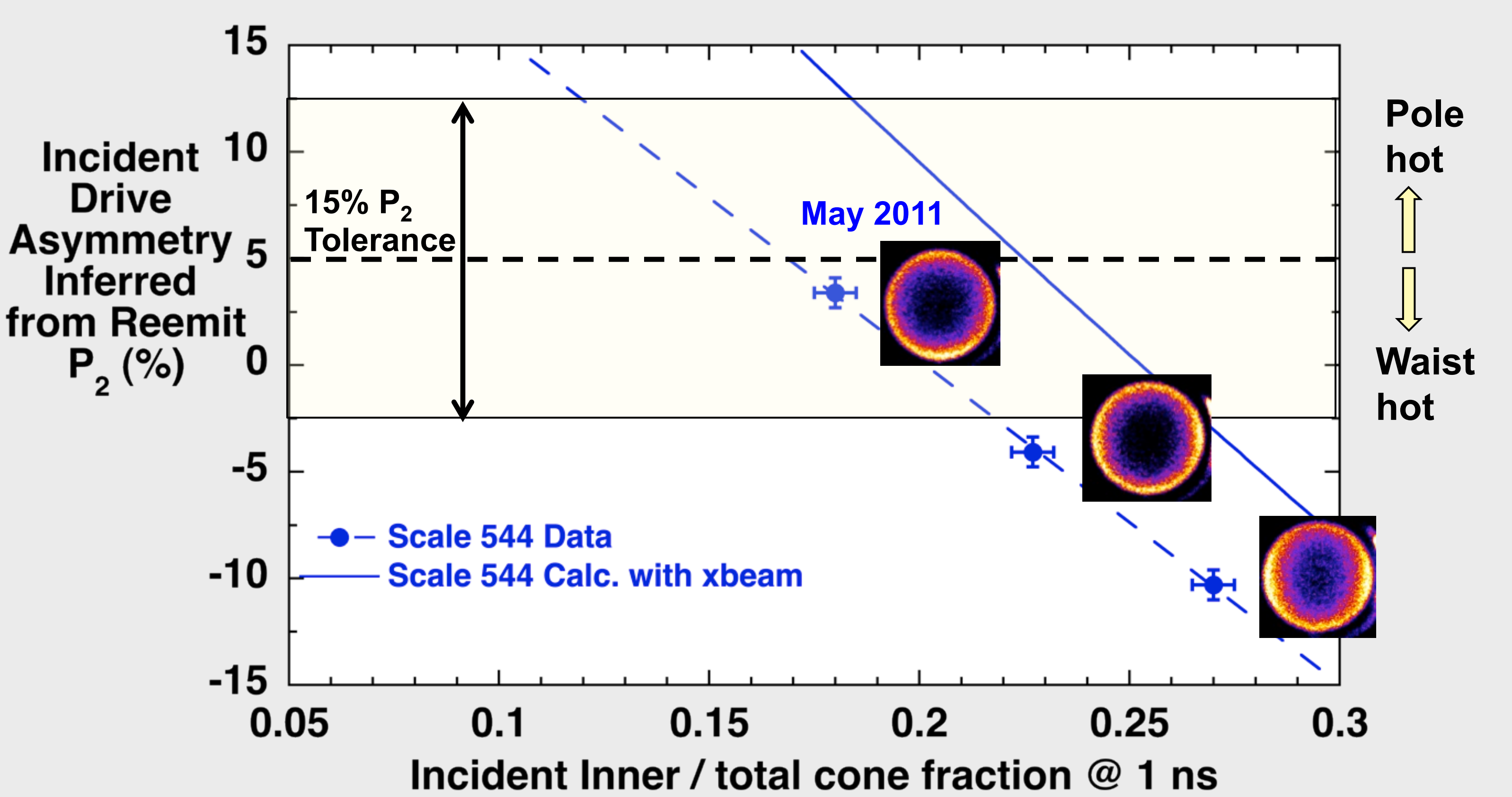
Bi sphere "Reemit" replaces layered capsule



Observable:
Limb brightness vs angle

May 2011: Re-emit brightness set picket cone fraction to 1% in the Scale 544 hohlraums used before August 2011

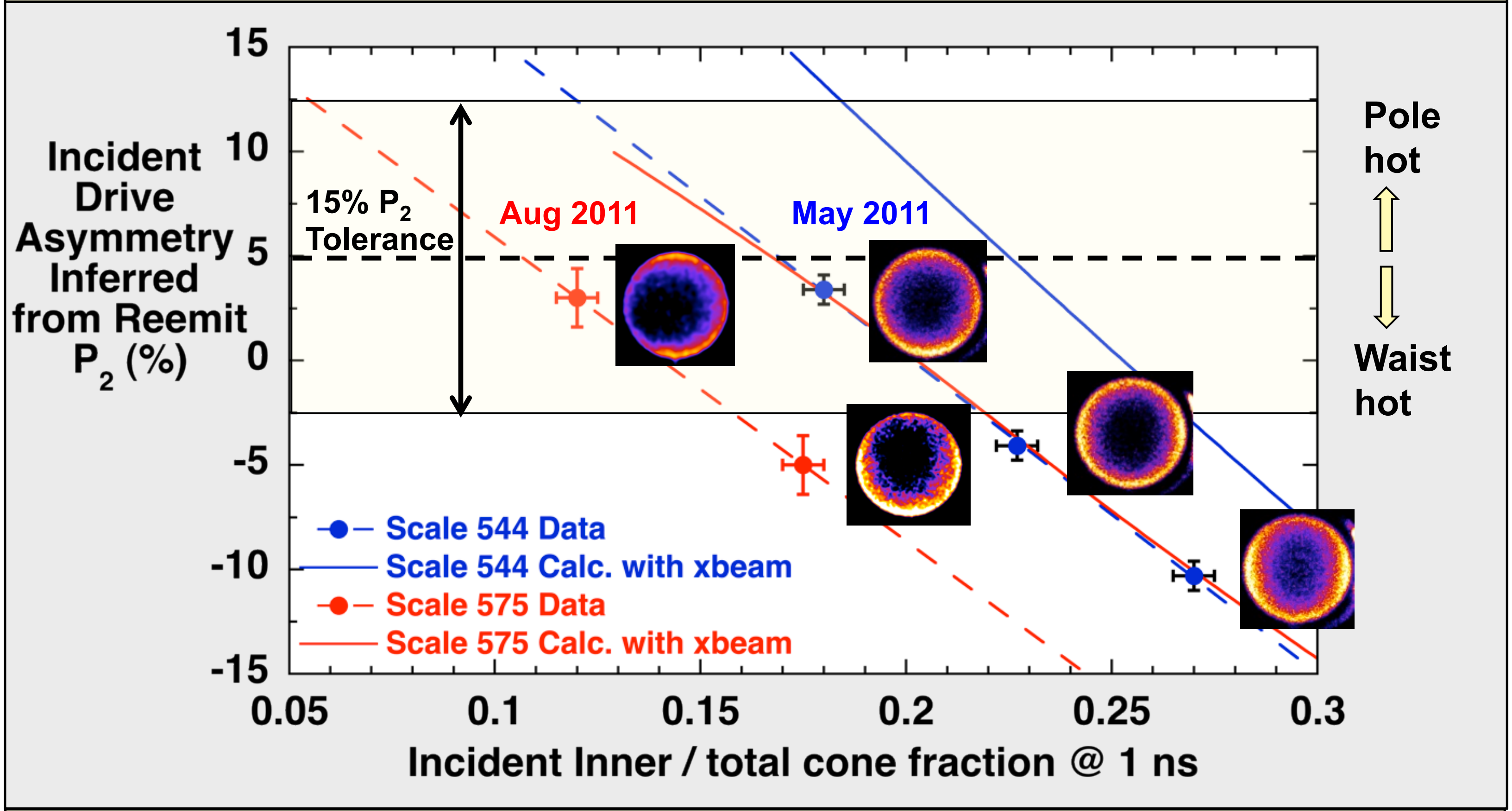
P_2 Foot Picket Flux Asymmetry vs. Foot Inner Cone Fraction



- Experiments showed larger cross-beam transfer than estimated using saturation parameter from peak power
- Experiments are better matched with no saturation

Aug 2011: Re-emit confirmed expected lower inner cone fraction for Scale 575 hohlraum

P_2 Foot Picket Flux Asymmetry vs. Foot Inner Cone Fraction

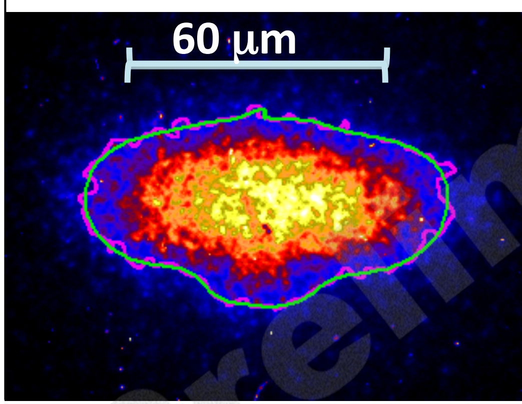


Optimum CF decreased from 0.18 to 0.10 because outers closer to equator

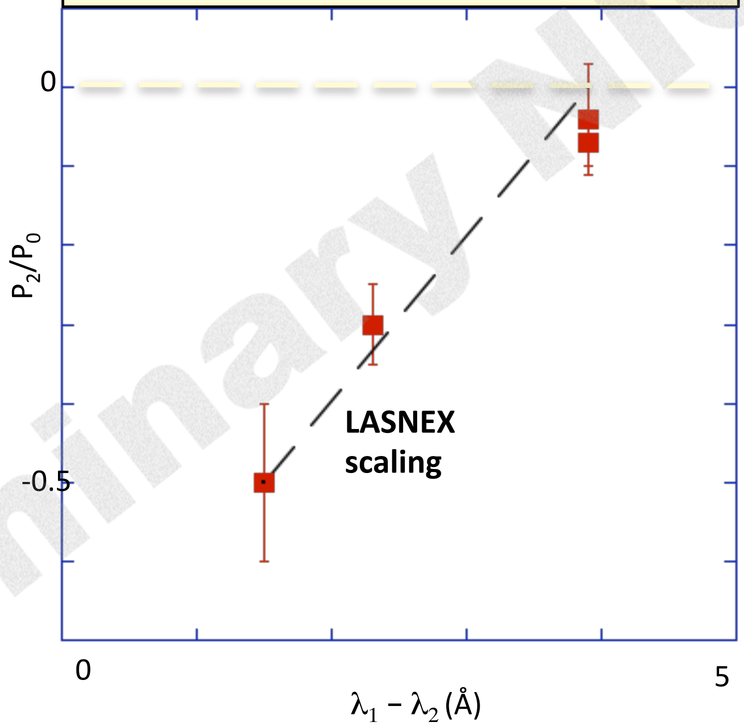
Implosion symmetry at the peak of the laser pulse is achieved by tuning the wavelength of the outer cone

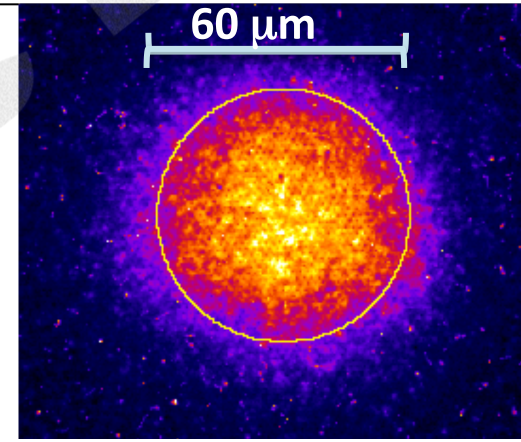
First demonstrated in experiments at 500 kJ in 2009, tuning the Δλ between inner and outer beams allows us to optimize implosion symmetry without changing the laser cone fraction

P2/P0 = -0.5,
P4/P0 = 0.3



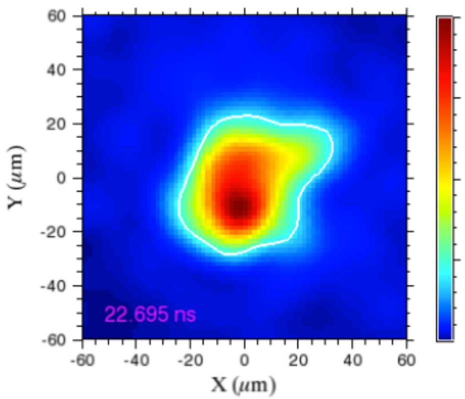
P_2/P_0 versus Δλ at 500 kJ scale

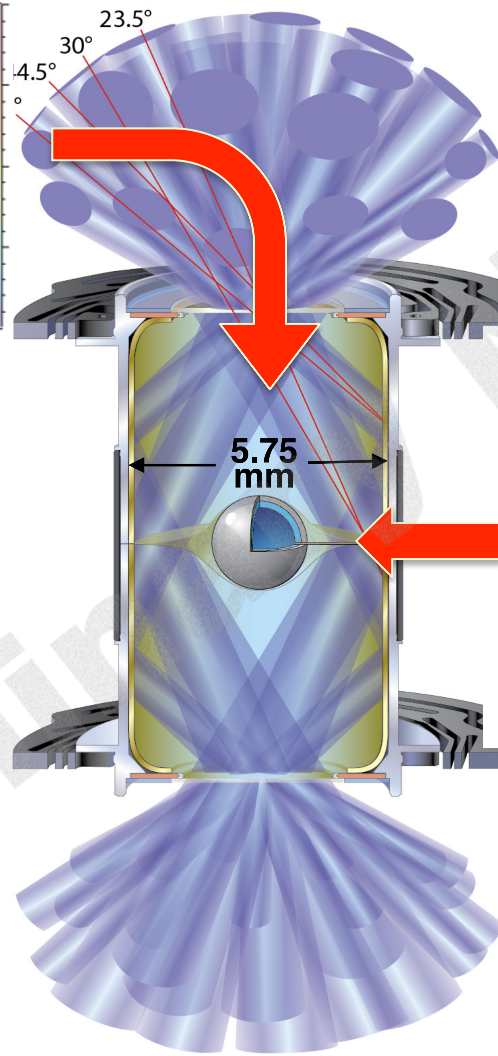


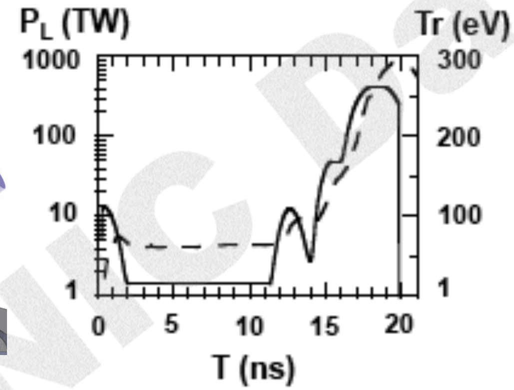


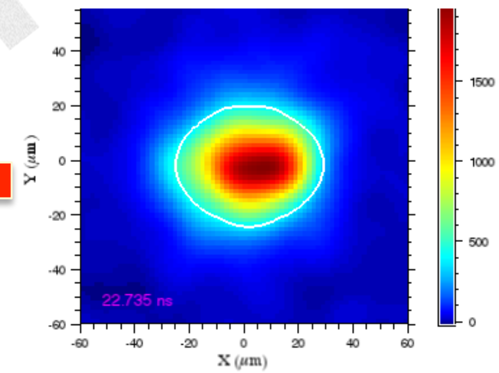
P2/P0 = -0.07,
P4/P0 = -0.03

Hot spot symmetry demonstrated in recent implosions is very close to the ignition specs





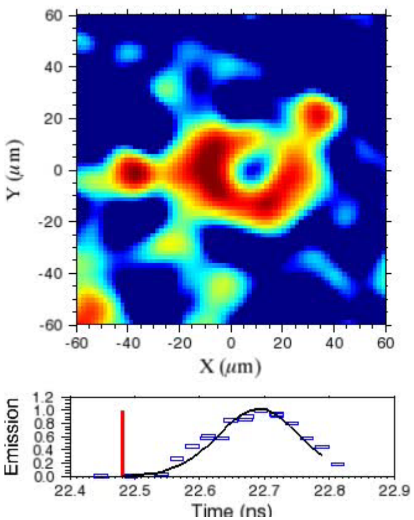


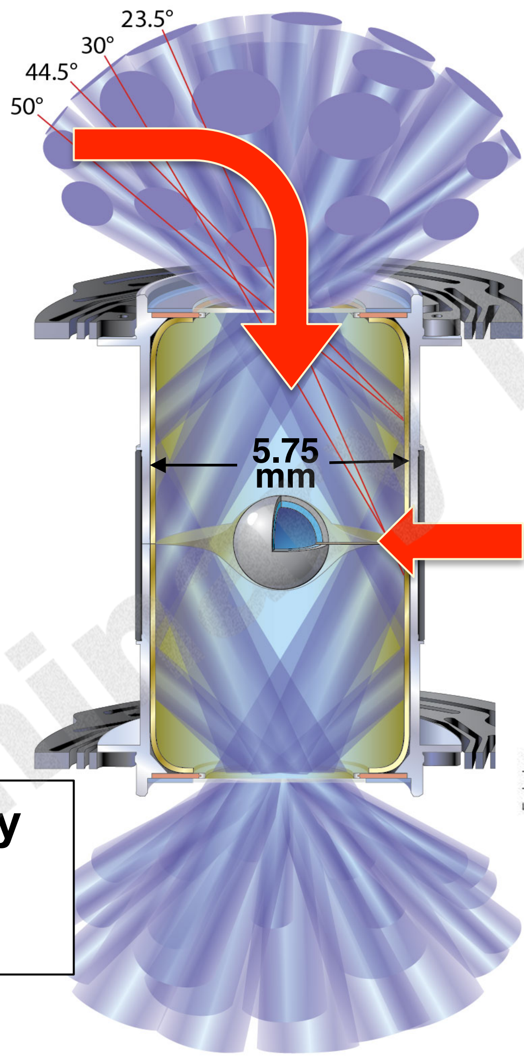


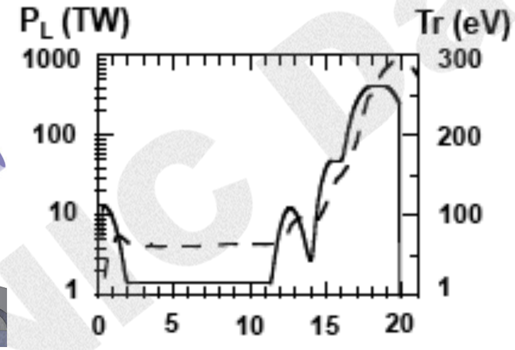
There is often a feature in the polar x-ray images which may be associated with fill tube

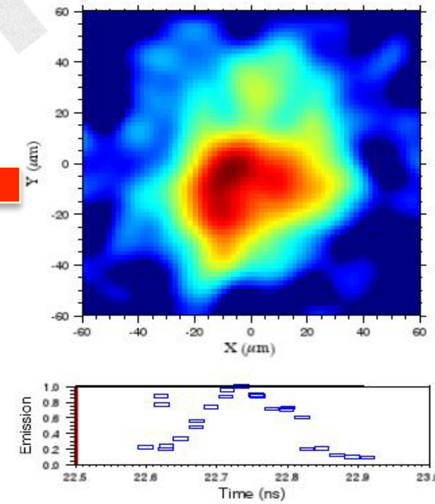
Symmetry at the peak of the pulse for shot 120205: 1.45 MJ pulse, 420 TW, 3 ns rise

Hot spot symmetry demonstrated in recent implosions is very close to the ignition specs









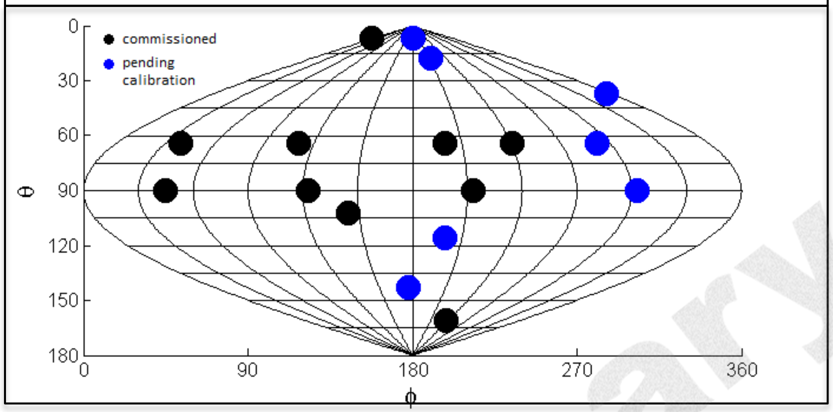
Time history of symmetry for shot 120205: 1.45 MJ pulse, 420 TW, 3 ns rise

NEW-Hohlraum-062810

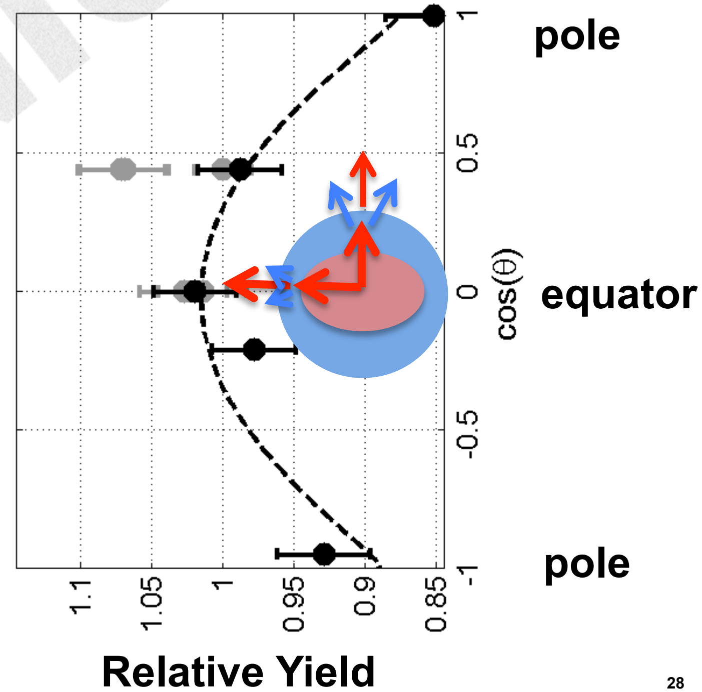
Nuclear measurements indicate that the main fuel can have large ρR variations even when the hot spot appears quite symmetric

FNADS (Flange Nuclear Activation Detectors) are Zirconium threshold detectors which measure the primary neutron yield

Multiple pucks around chamber



Count activation and analyze (sometimes large asymmetry)

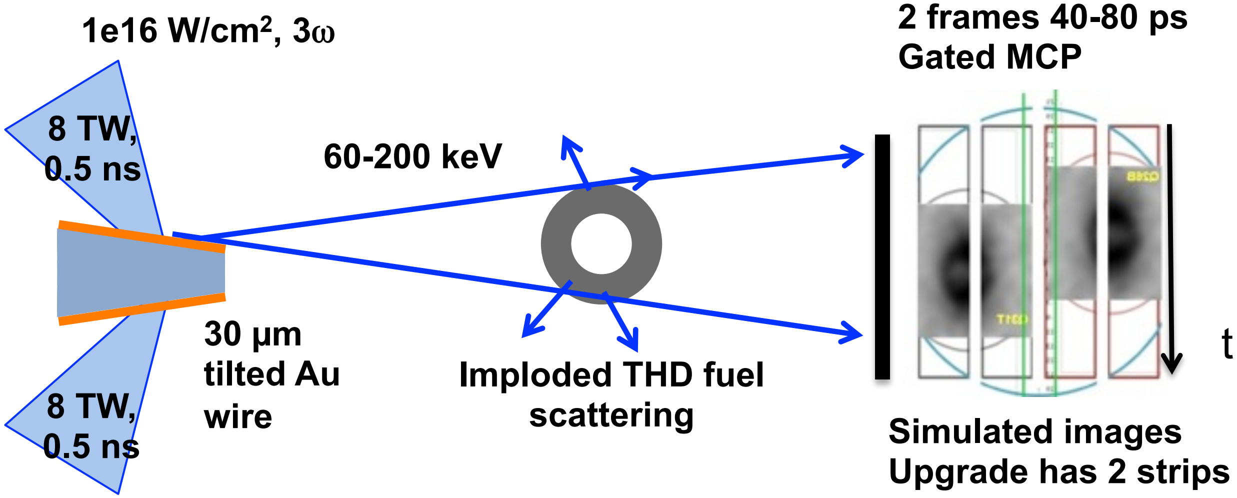


- Some shots show significant signal variations (high ρR on poles) – on a typical shot with ρR~1 g/cm^2 in DT, about 20% of the neutrons are downscattered, so a 10% variation in the measured primary yield corresponds to a 50% ρR variation (needs better calibration for required accuracy)
- ρR variations also indicated by Neutron Time of Flight (NTOF) and Magnetic Recoil Spectrometer (MRS) data

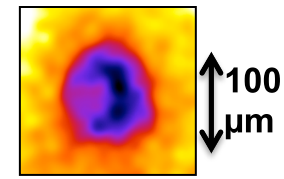
We are developing imaging diagnostics which will give us improved shell-in-flight and compressed fuel measurements

NIC

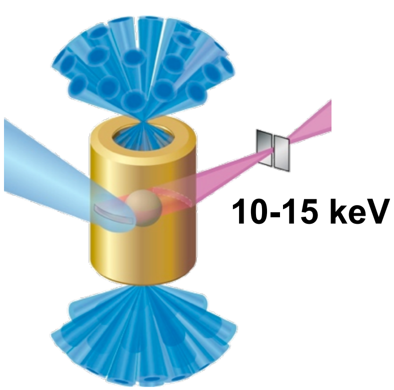
Compton radiography – DT fuel at stagnation

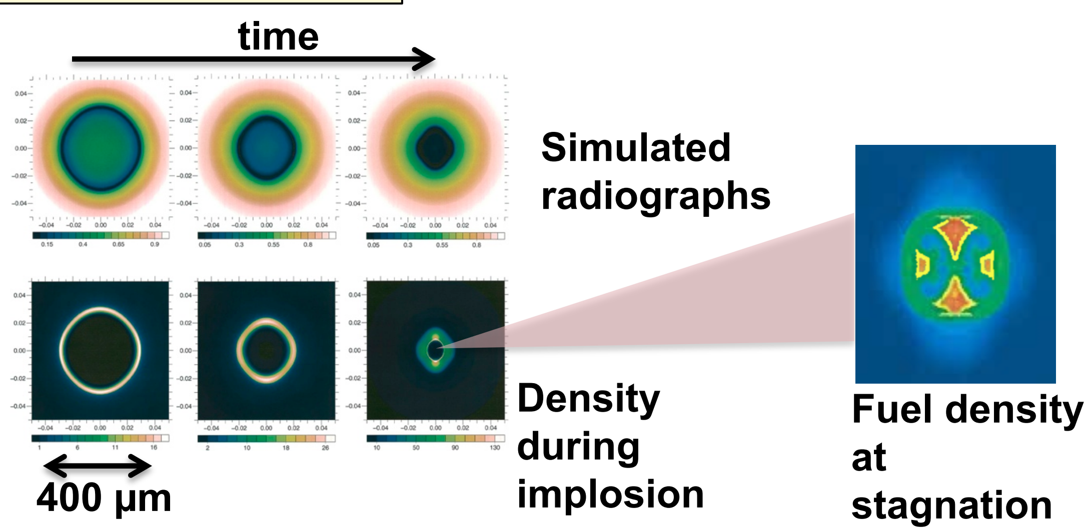


Demonstrated at OMEGA

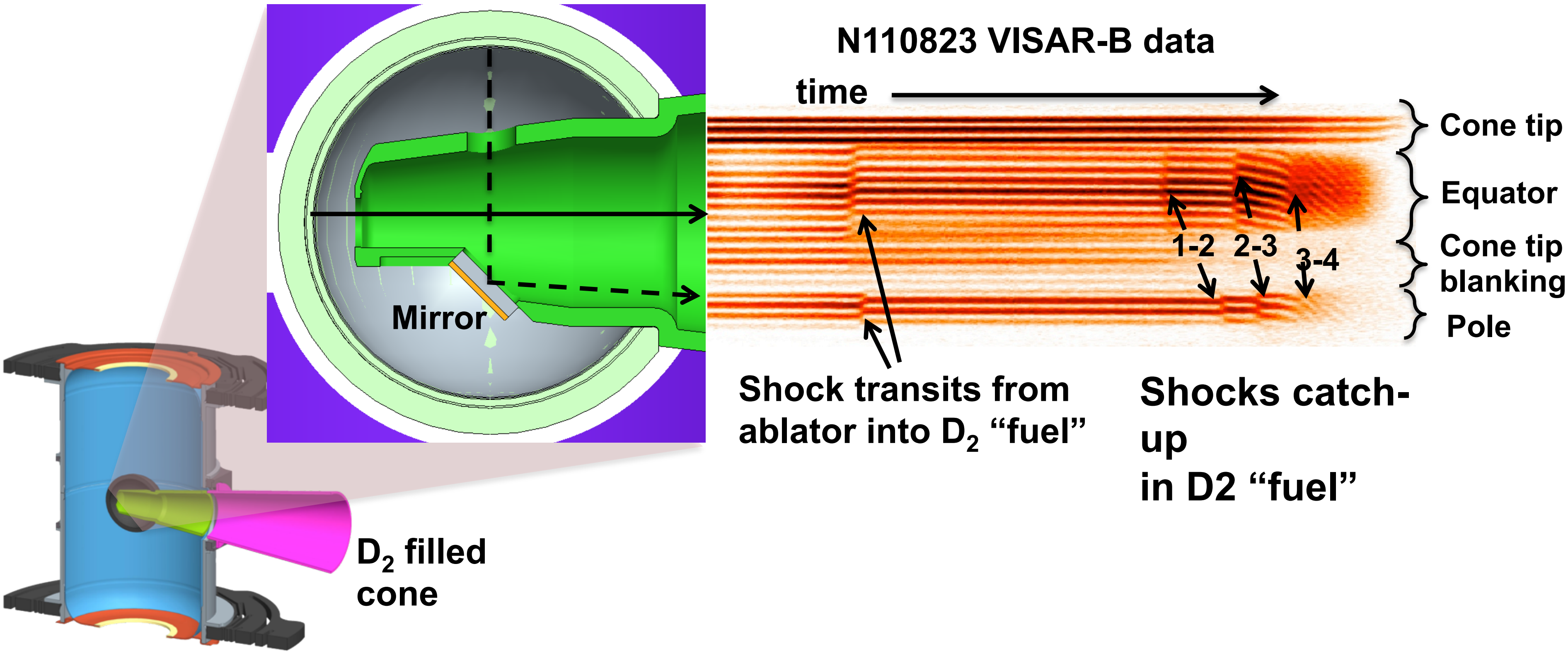


2D absorption radiography – shell in-flight





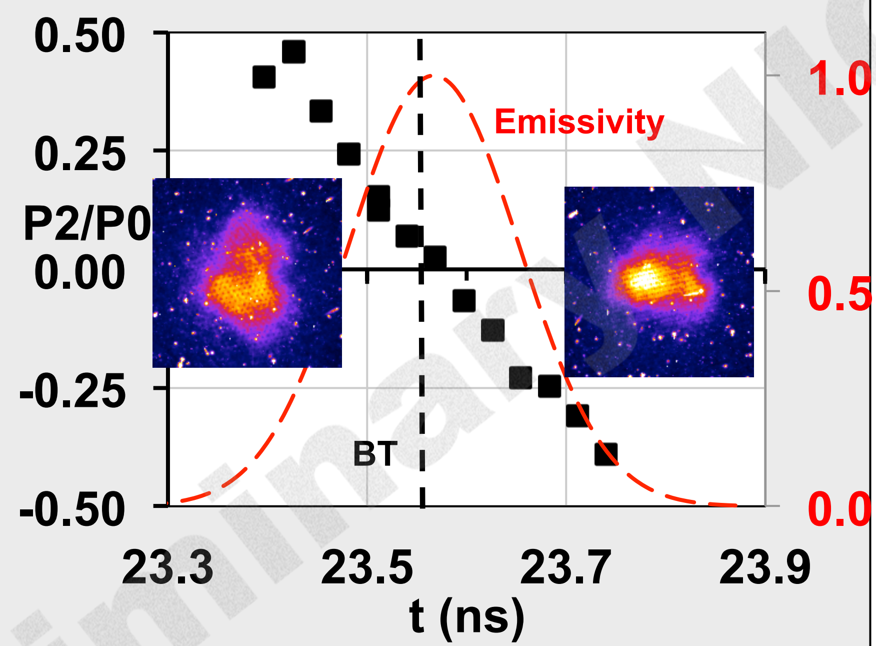
The mirrored keyhole targets are used to optimize shock timing and velocity as well as the pole to waist asymmetry for all 4 shocks in the pulse



Calculations show that asymmetric 2nd and 3rd shocks give rise to symmetry swings in the imploded core

Shock asymmetries can lead to P_2 swings in core shape and fuel ρr nonuniformities

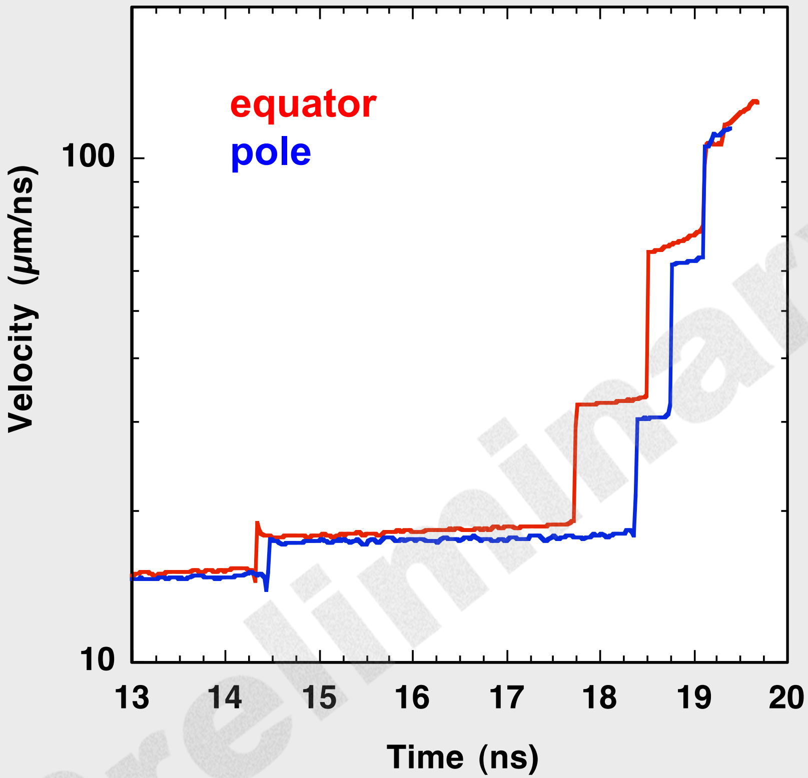
Example of measured THD core X-ray P2/P0 evolution near bangtime



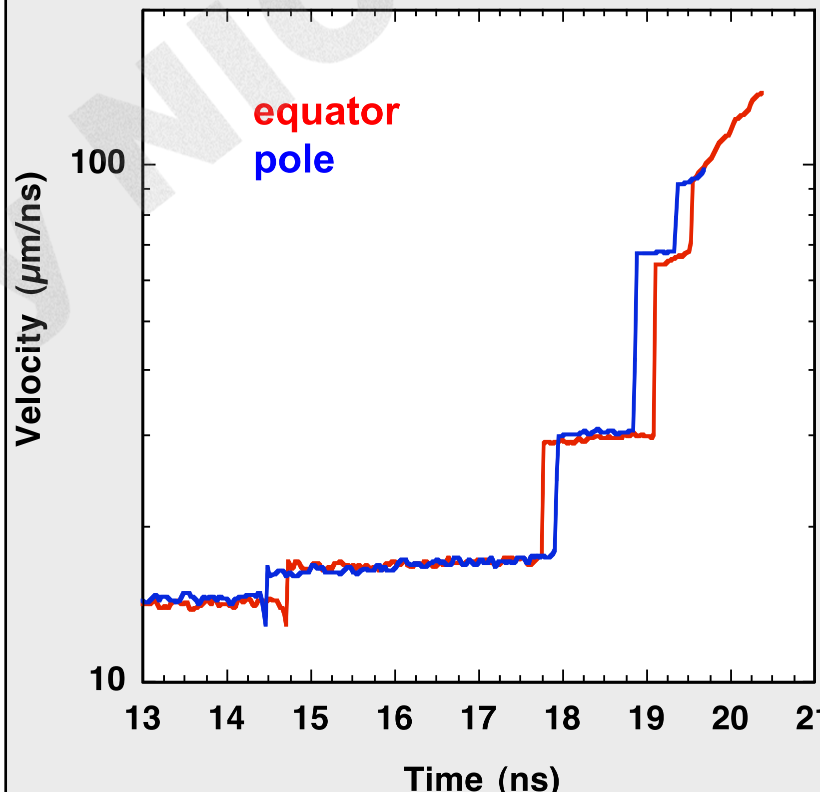
Future: Check if reduced P_2 swings in final core compression phase

Mirrored keyhole experiments were used to improve the shock symmetry

Before 2nd and 3rd cone fraction tuning	*After* 2nd and 3rd cone fraction tuning
N110823 VISAR data	N111027 VISAR data



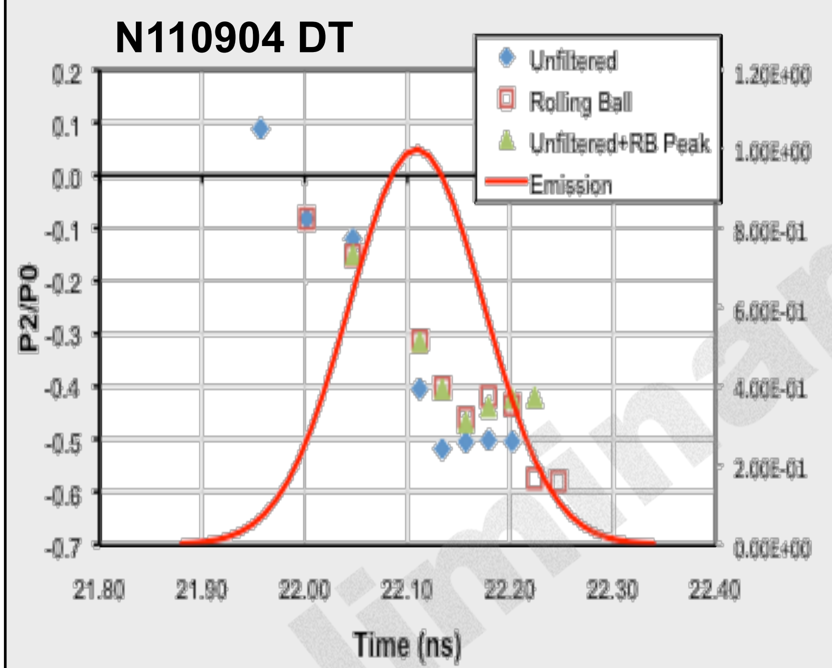
2nd and 3rd shocks out of spec



2nd and 3rd shocks in spec

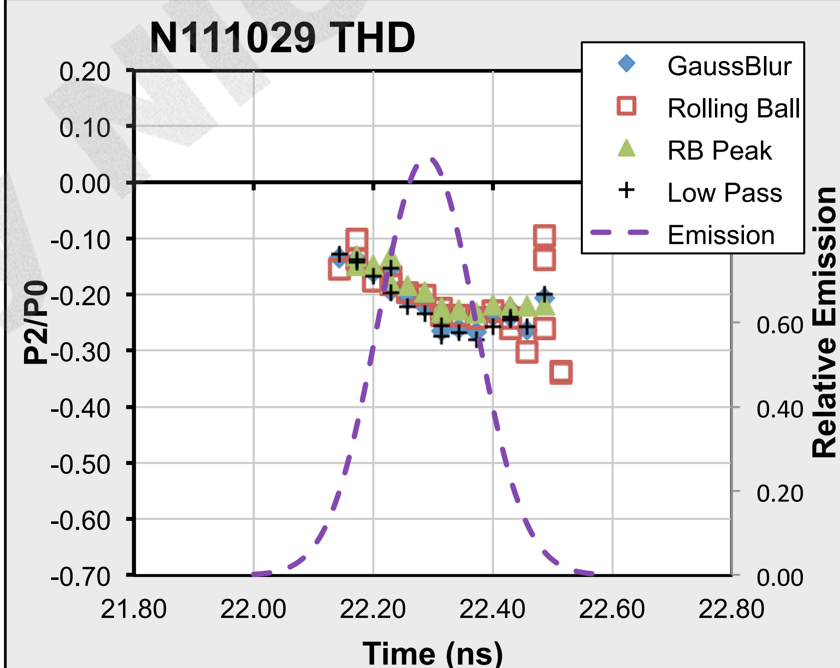
Swings in symmetry are reduced after 2nd and 3rd cone fraction optimization

Before 2nd and 3rd cone fraction tuning



Large swing in P2 vs time

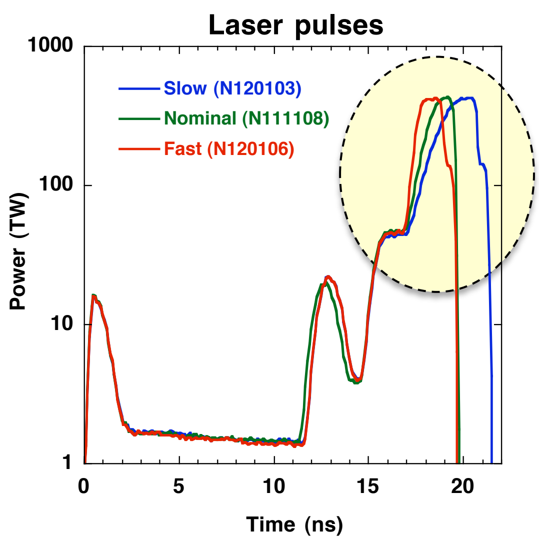
After 2nd and 3rd cone fraction tuning



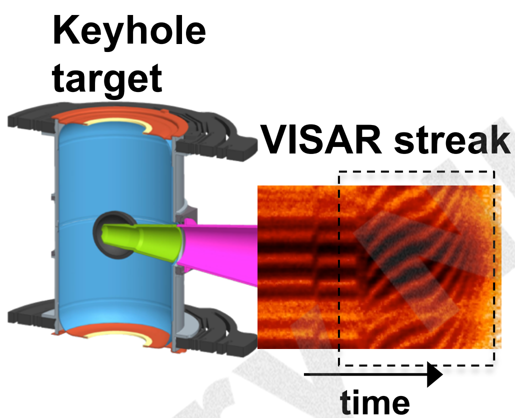
Modest swing in P2 vs time

The first tests of the impact of variations in the temporal shape of the peak power pulse changed the rate of rise to peak power

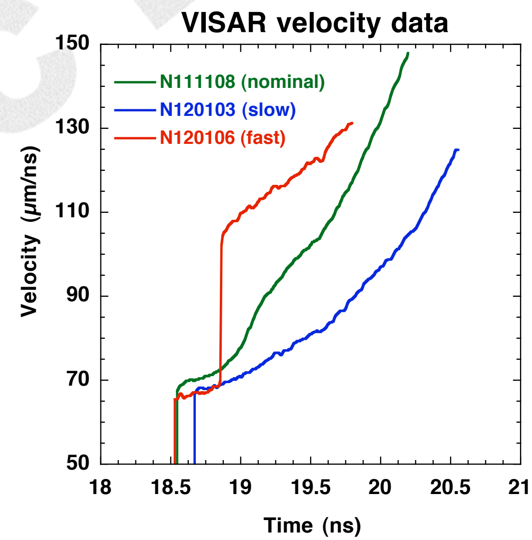
4th pulse rise variation



1ns (fast)
2ns (nominal)
3ns (slow)



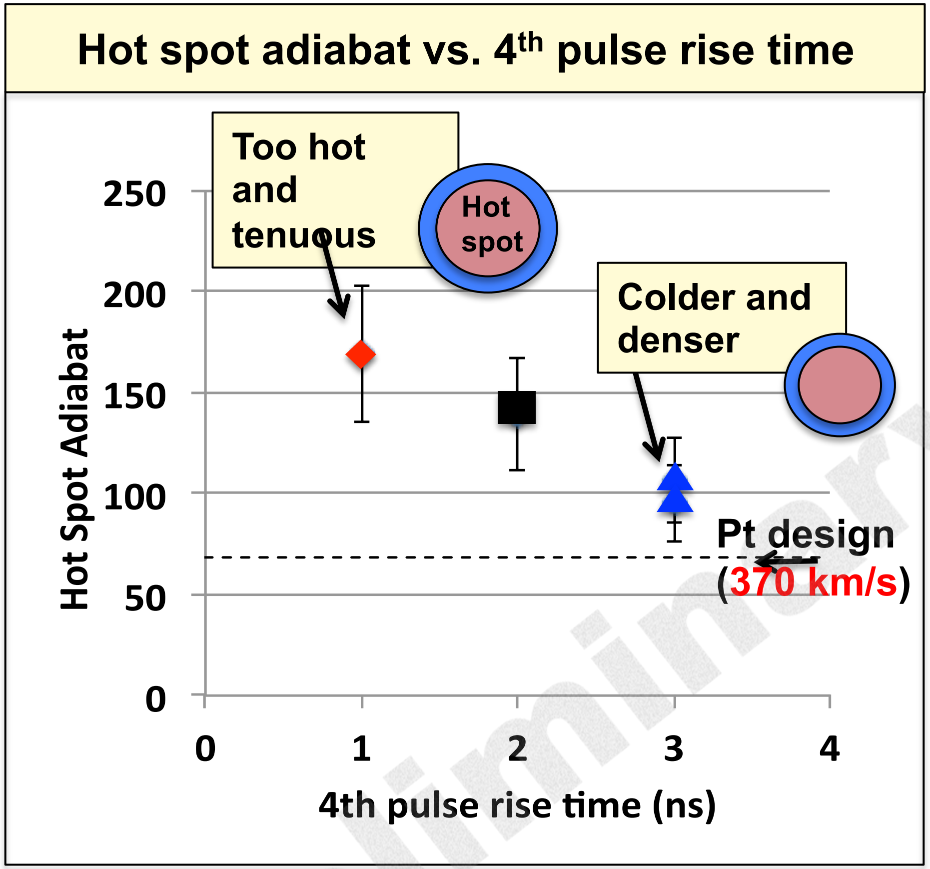
4th shock velocity

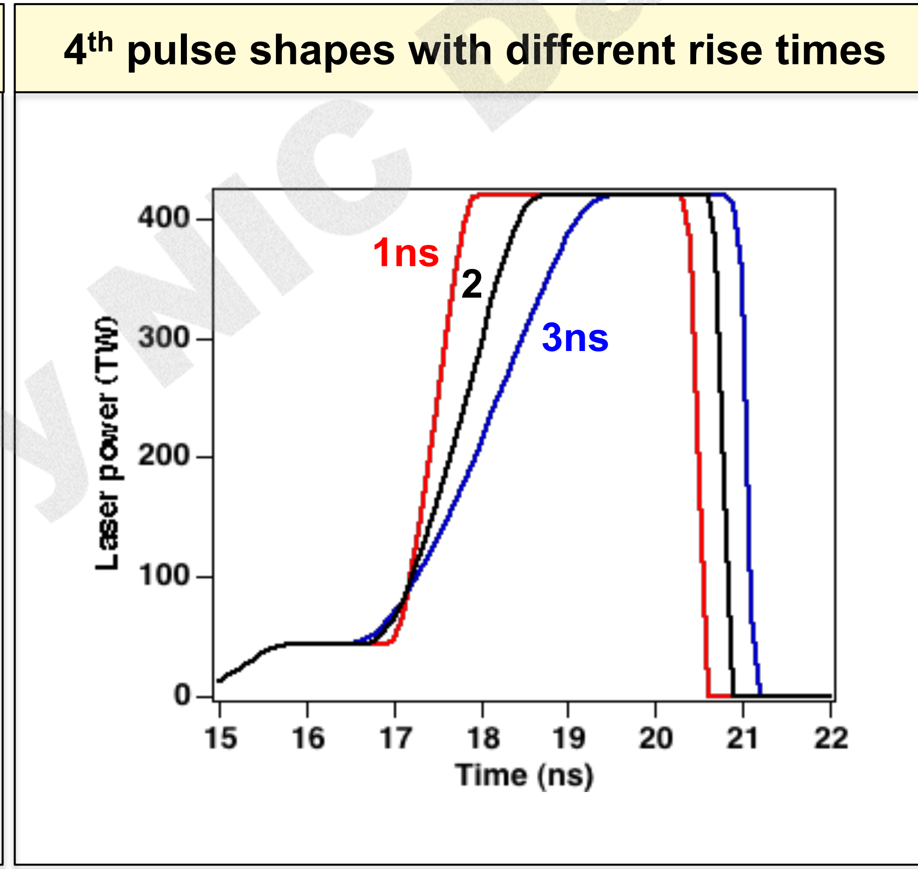


1ns (fast)
2ns (nominal)
3ns (slow)

Slower rise pulses are predicted to be less sensitive to fluctuations in drive in 4th rise

Slower rise 4th pulses have produced hot spot adiabats closer to ignition goals

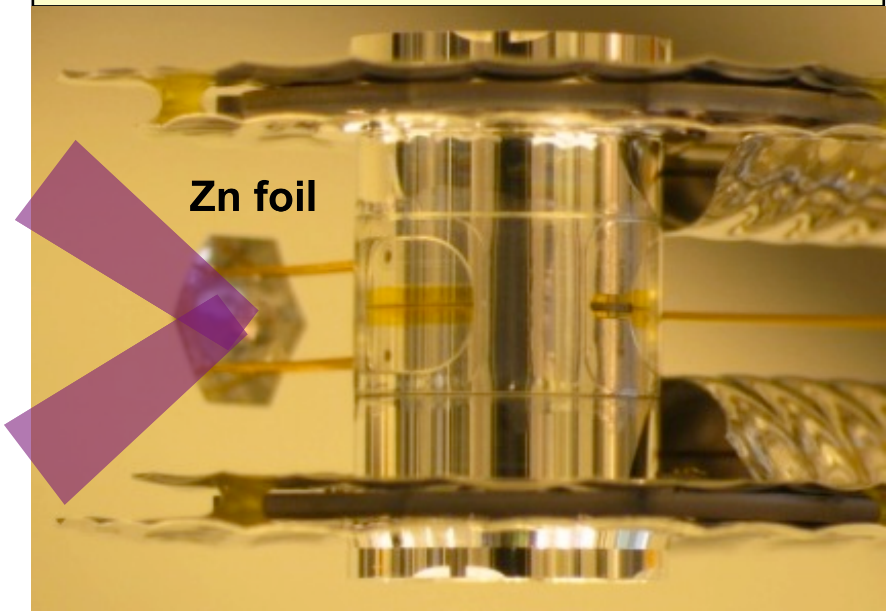




As a result of these tests, we adopted the slower "3ns rate of rise" as the primary pulse shape through April 2012

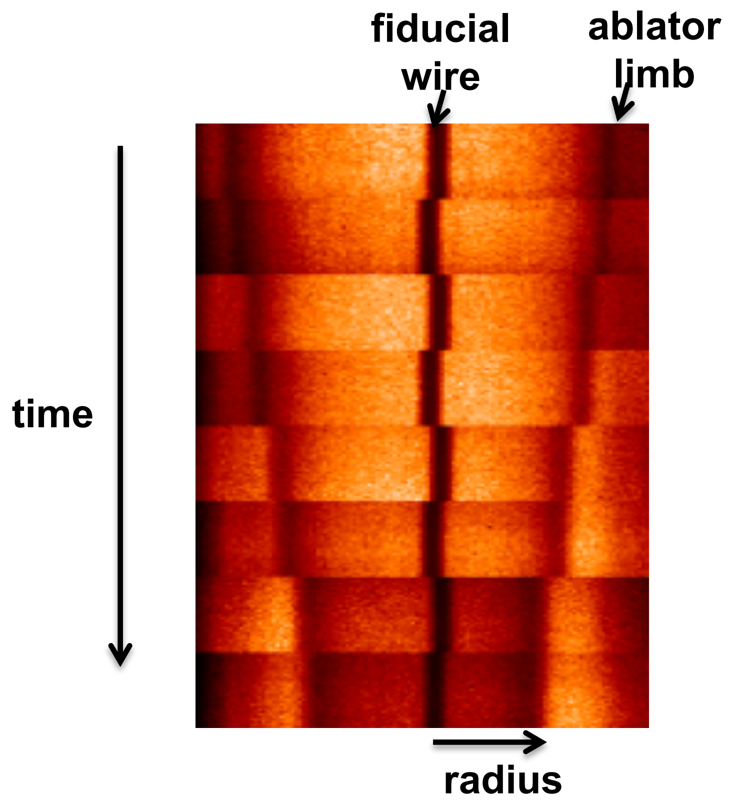
Backlit Capsule sets peak power and capsule ablator thickness (trading off velocity vs mix susceptibility)

Capsule backlit by x-rays from separate laser plasma



Until March 2012, implosion kinematics were measured using gated backlit radiography

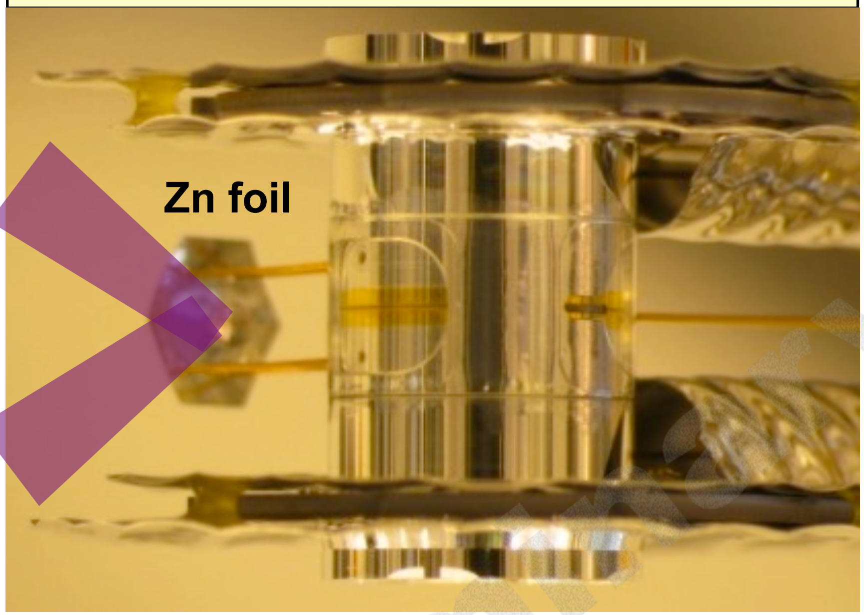
9 keV gated radiograph



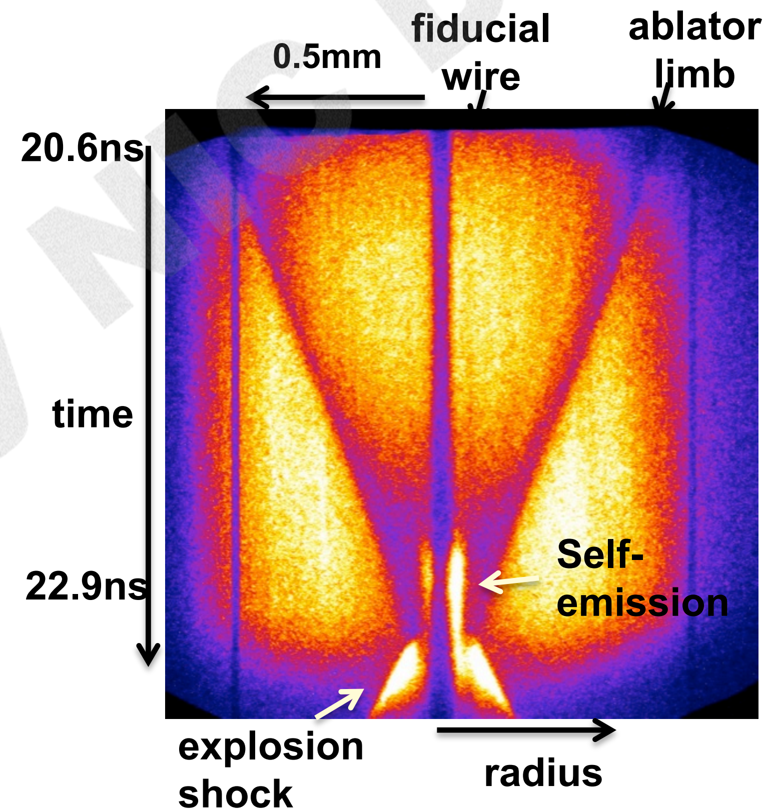
Technique measures shell radius, velocity, ρR profile, and remaining ablator mass

In March, we activated streaked backlit radiography (3/24/12)

Capsule backlit by x-rays from separate laser plasma



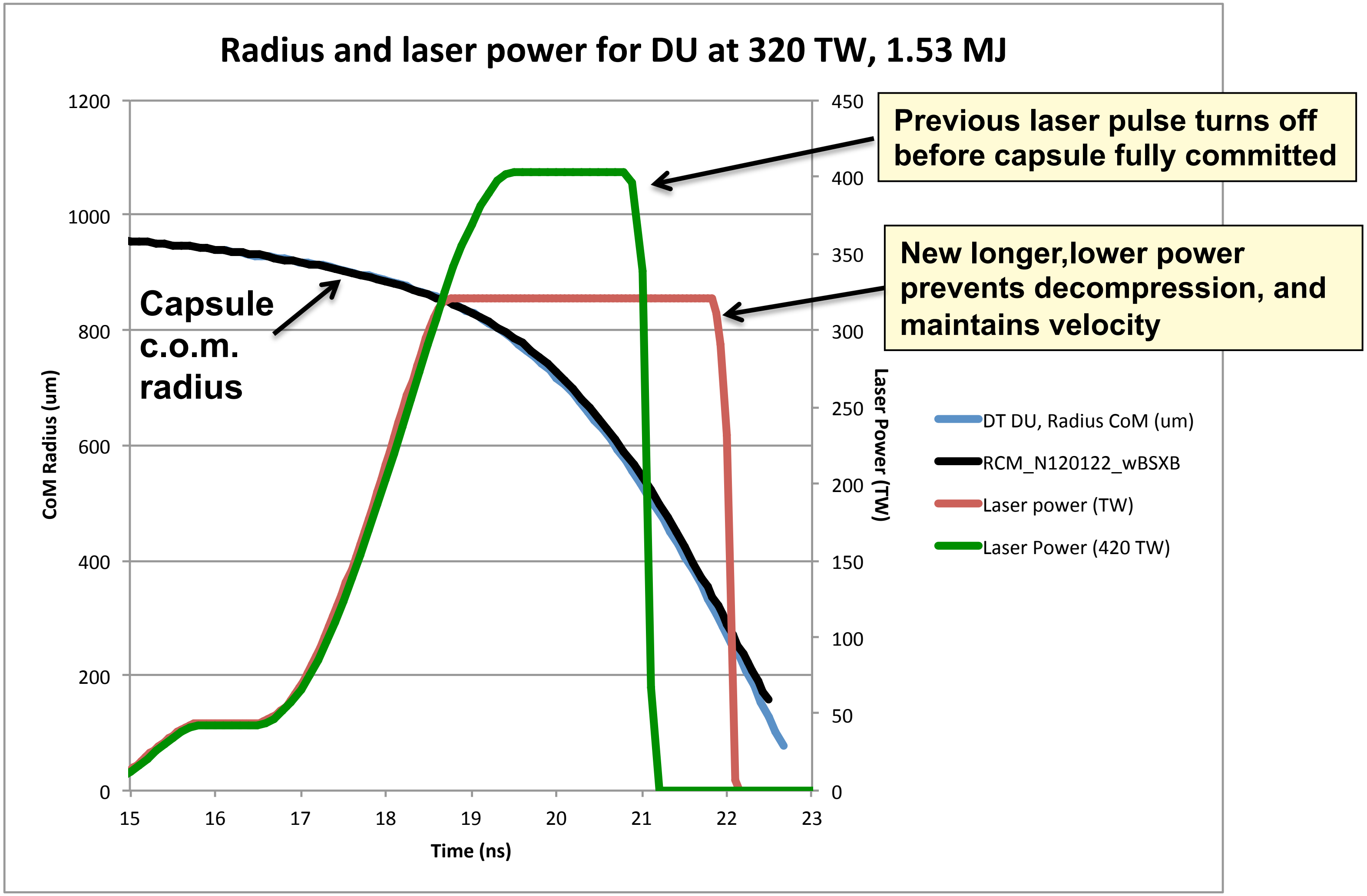
9 keV streaked radiograph



Provides continuous record of ablator kinematics

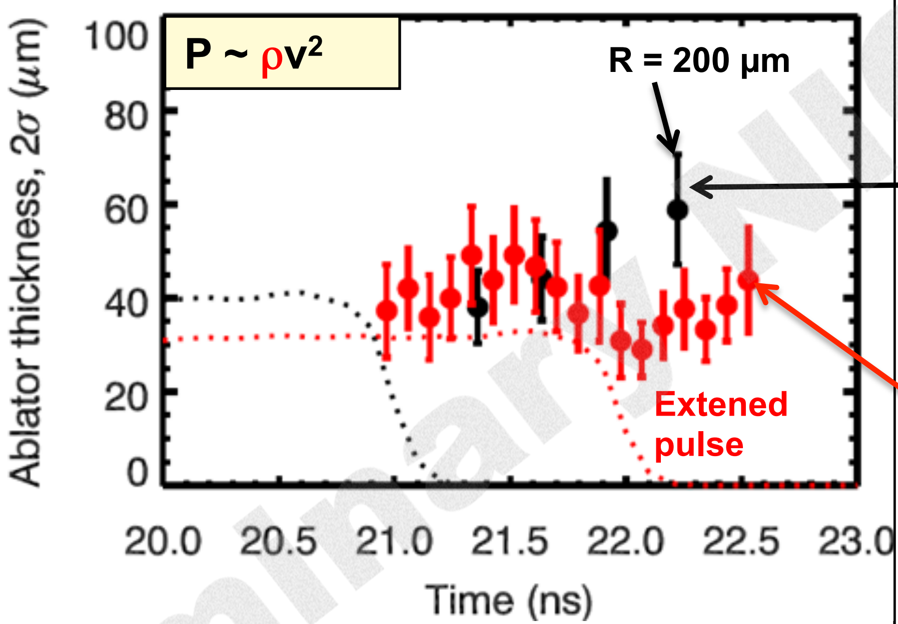
In March, experiments moved to longer "no-coast" pulse to avoid capsule decompression prior to stagnation

Simulated capsule center of mass radius vs time



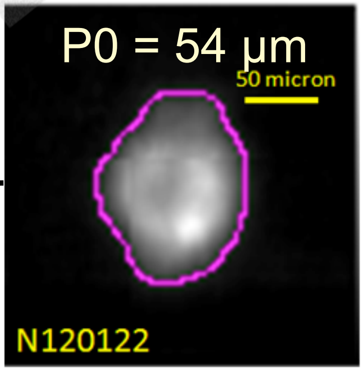
"No Coast" behavior: Ablator stays compressed by extending pulse out to r = 300 μm

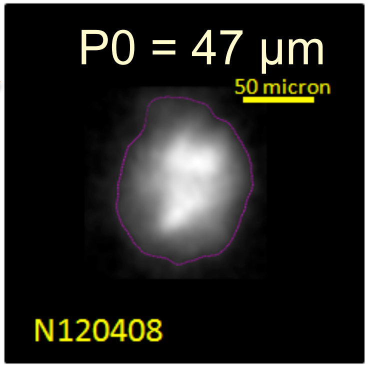
Ablator width vs. time



Maintaining the drive prevents shell from decompressing -> higher stagnation pressure

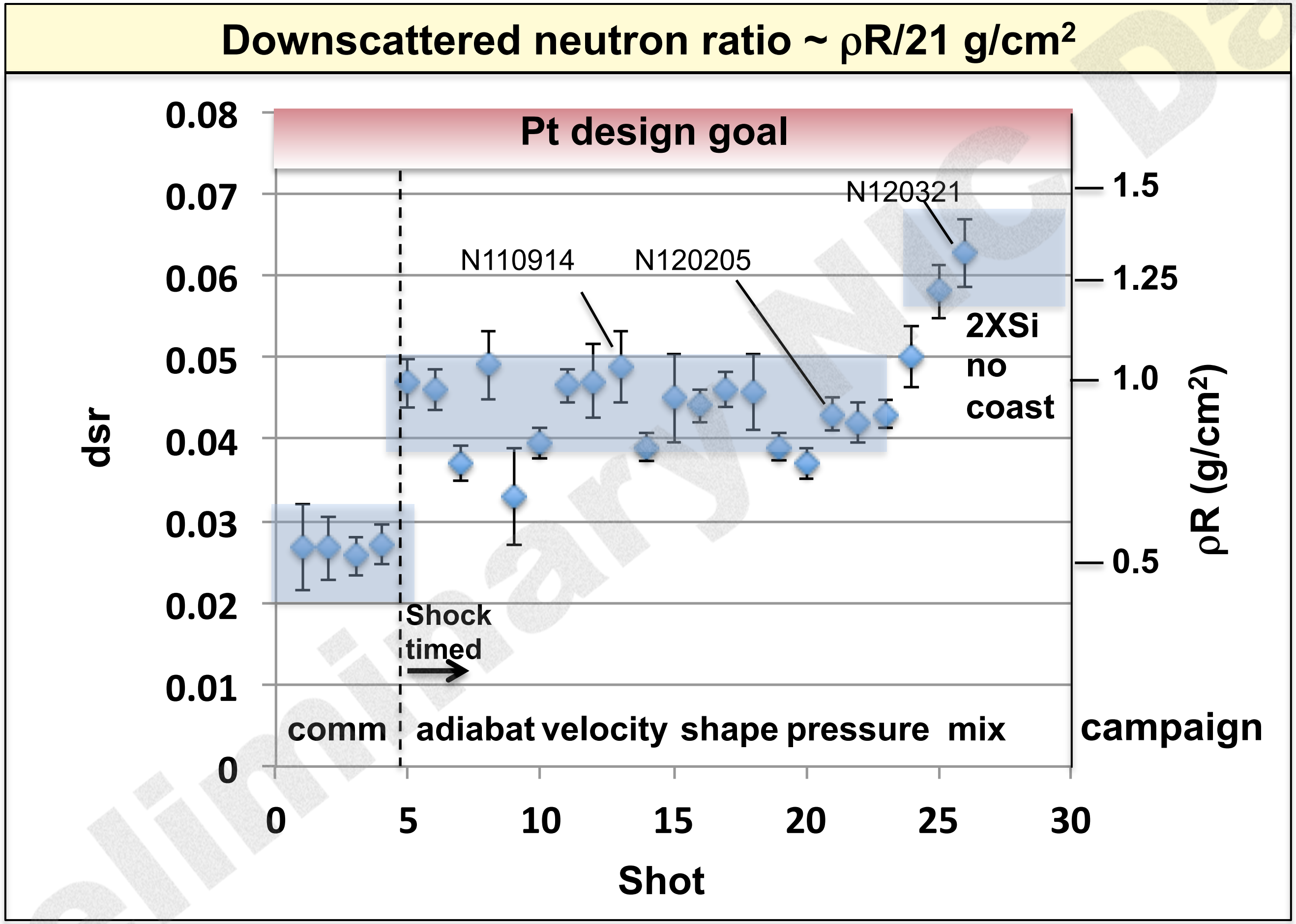
Coast vs No coast X-ray cores





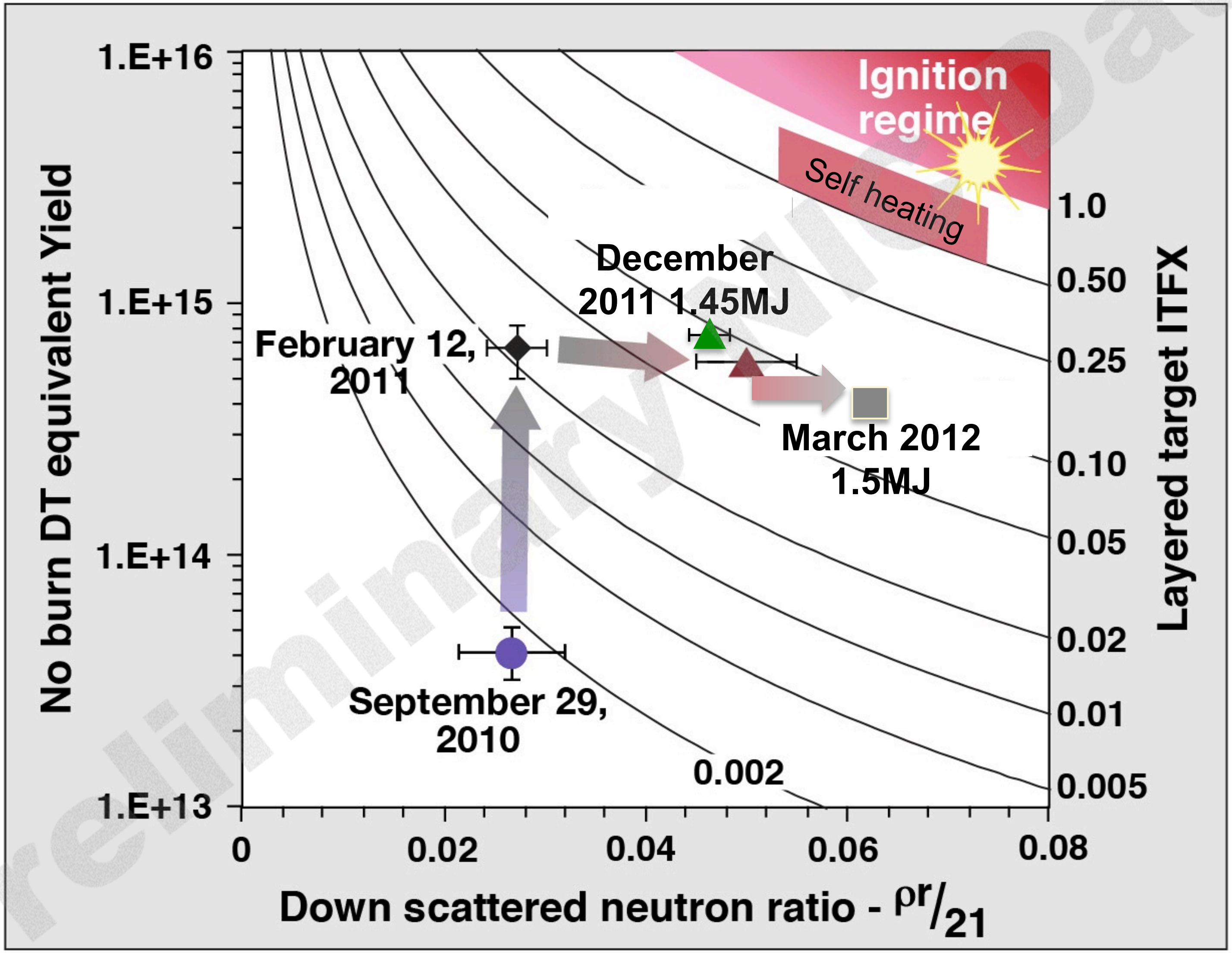
No Coast core size is 13% smaller
~50% higher pressure

Feb-March 2012 Campaigns increased down scattered neutron ratio (dsr) ~ ρR / 20

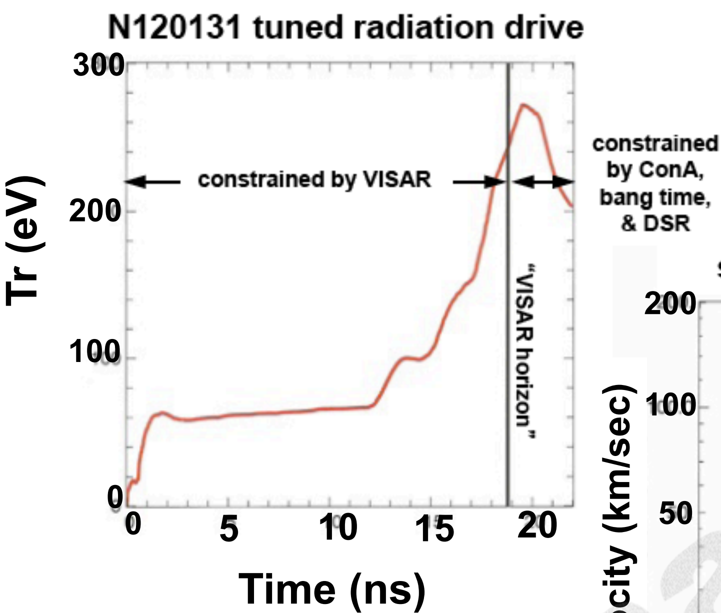


Recent improvement attributed to reduction in coasting (longer laser pulse) and reduction in interface mix (2XSi dopant in ablator reducing preheat)

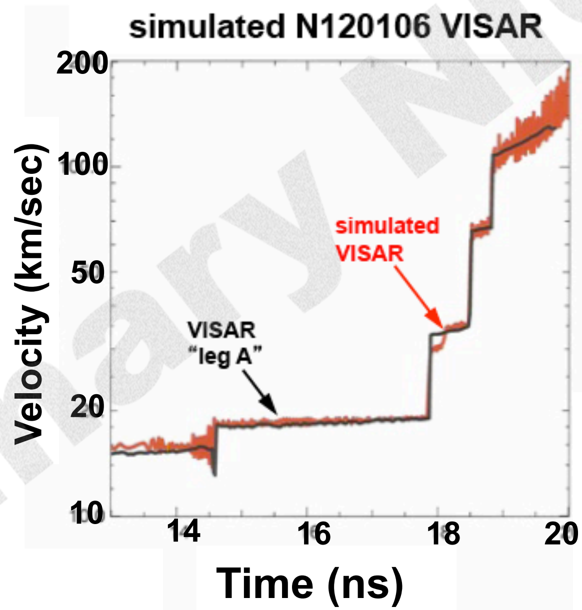
Fuel ρr is now at about 85% of the ignition point design but we need to increase yields a factor of 5-10 to get into the strongly self-heated regime

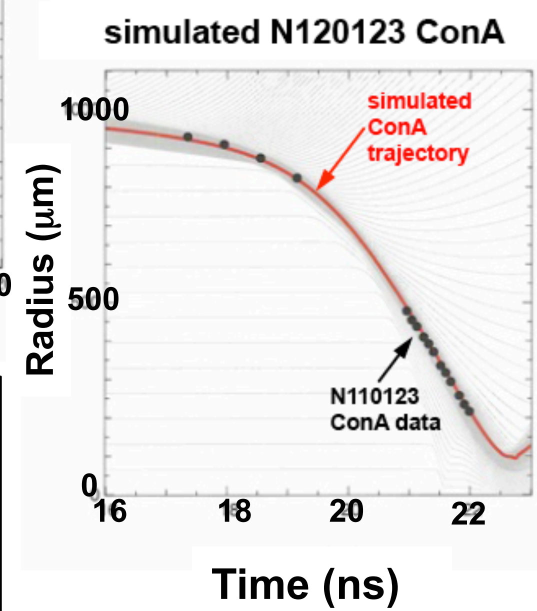


We have developed a standardized approach for generating 1D capsule drives used in calculating cryo-layered capsule performance



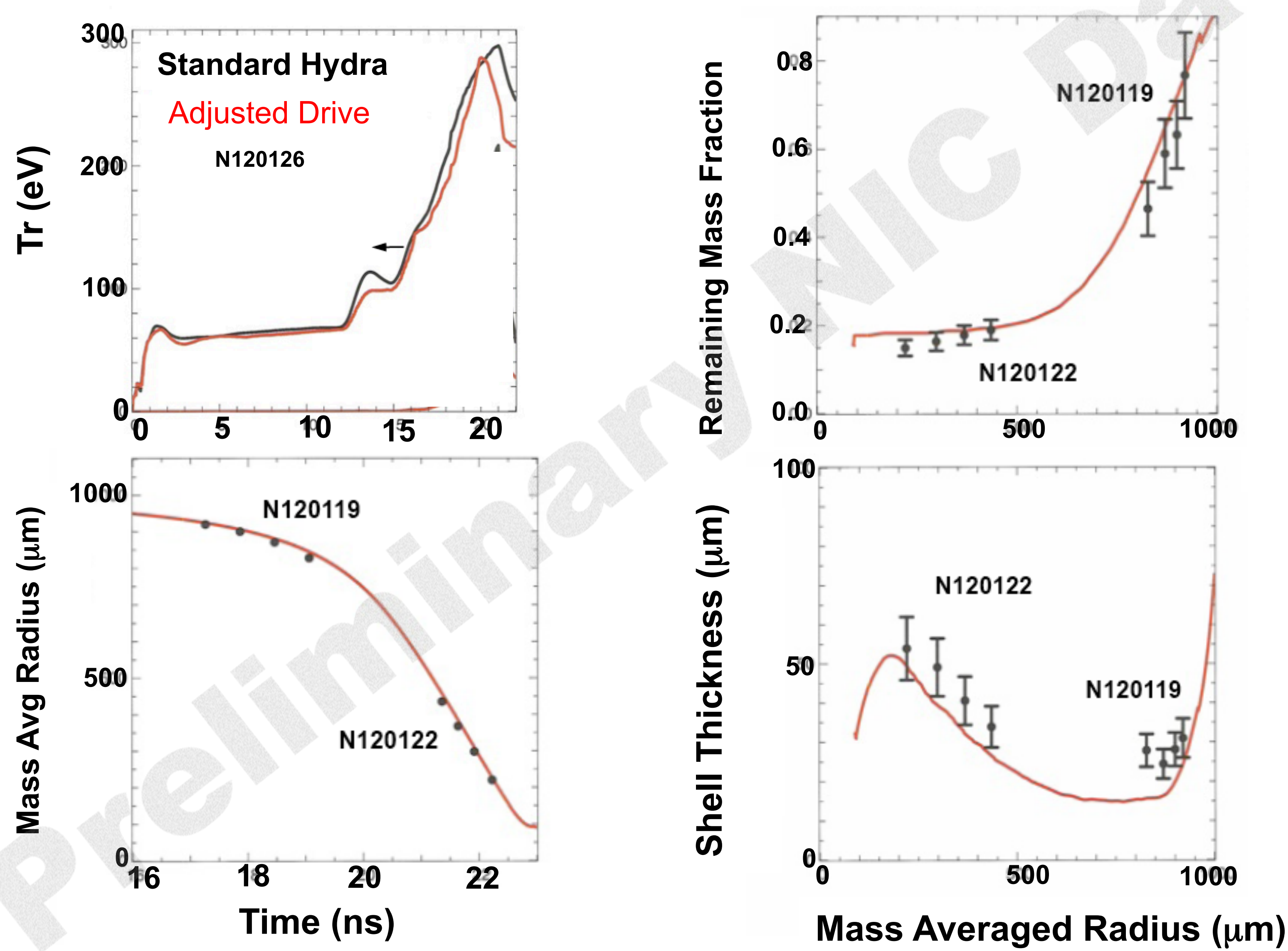
The radiation drive is modified so that the calculation matches the visar and Convergent Ablator Data



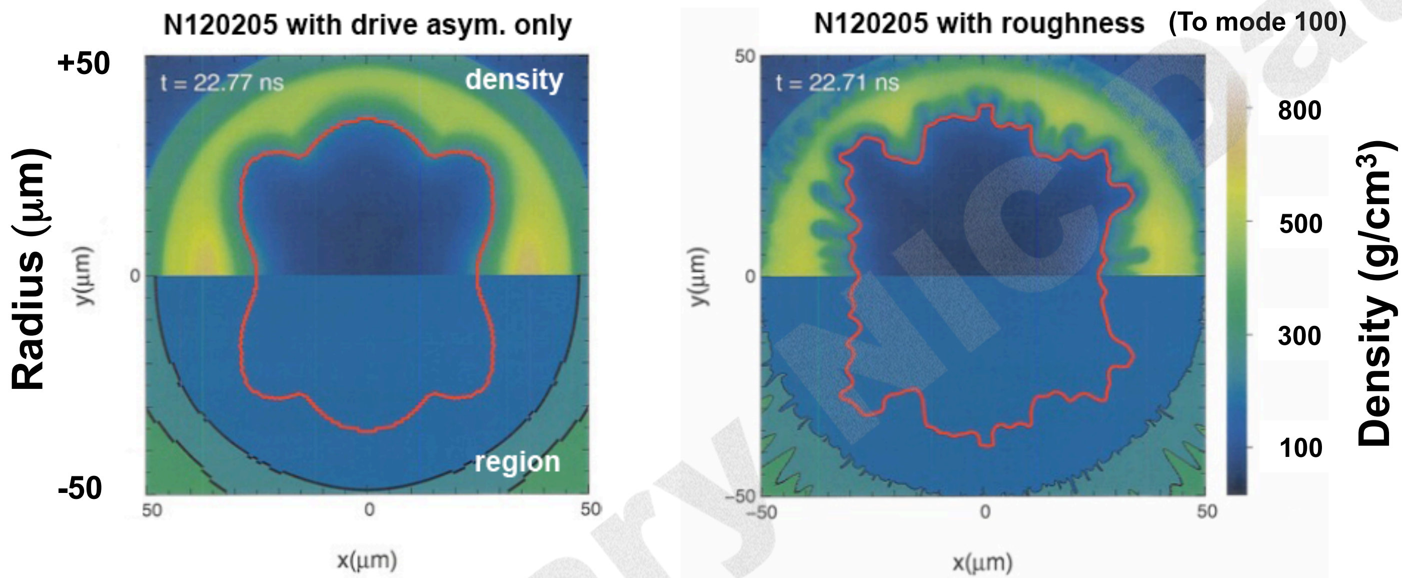


This approach allows us to explore the incremental differences between the models and the data as we move through the implosion process and to correct for those differences as we move forward

When the drive is adjusted to match the keyhole data and the shell radius versus time, the remaining mass and shell thickness are also matched within the error bars



Calculations of layered implosions with these modified drives match much of the observed data but typically over estimate yields by a factor of several



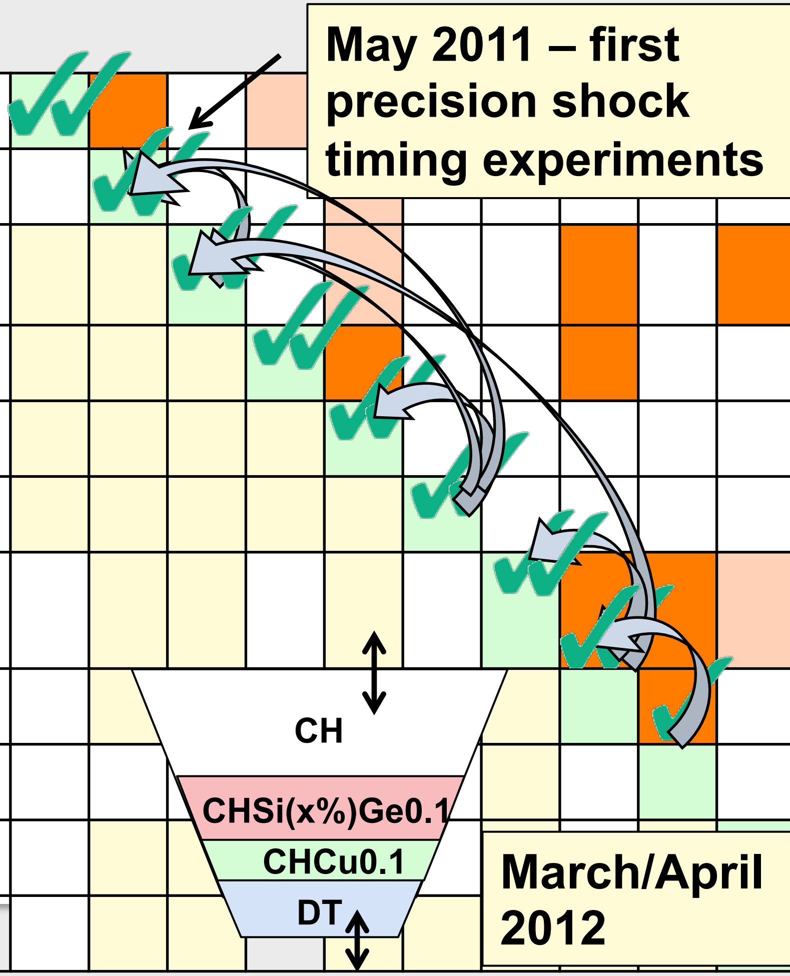
	DSR (%)	P_0 (µm)	P_2/P_0	HS pres. (Gbar)	HS den. (g/cm^3)	HS mass (µg)	T_{ion}(keV)	neutrons (10^{14})
1-D*	4.41	—	—	176.6	80.9	6.70	2.90	22.9
asym. only*	4.95	25.15	- 0.05	212.6	92.8	7.49	2.95	24.7
with tent & roughness*	4.60	25.36	- 0.05	161.2	71.6	3.59	2.91	17.8
N120205	4.54	22.89	- 0.15	105.1	44.3	4.80	3.39	5.64

* with α particle momentum and energy deposition switched off

- **Calculations do not include the known 3D long wavelength asymmetry in the capsule, hohlraum, and laser power**
- **3D calculations to mode 100 are under development**

We have just completed the first iteration on a mix campaign

Observables		Platform
Adiabat	Picket P2	Reemit
	Shock velocity/P2	Keyhole, THD/DT, CR, ConAWide
	Shock timing/dsr/ ρr	
Shape	Peak P2	Symmetry capsule or THD/ DT and CR
	Peak P4	
	Peak m4	
Velocity	Implosion Velocity	ConA, THDConA
Fuel Mix	Residual mass	
	M-band	Any implosion
Hotspot Mix	Growth factor	Mixcap
	Dopant emission	THD



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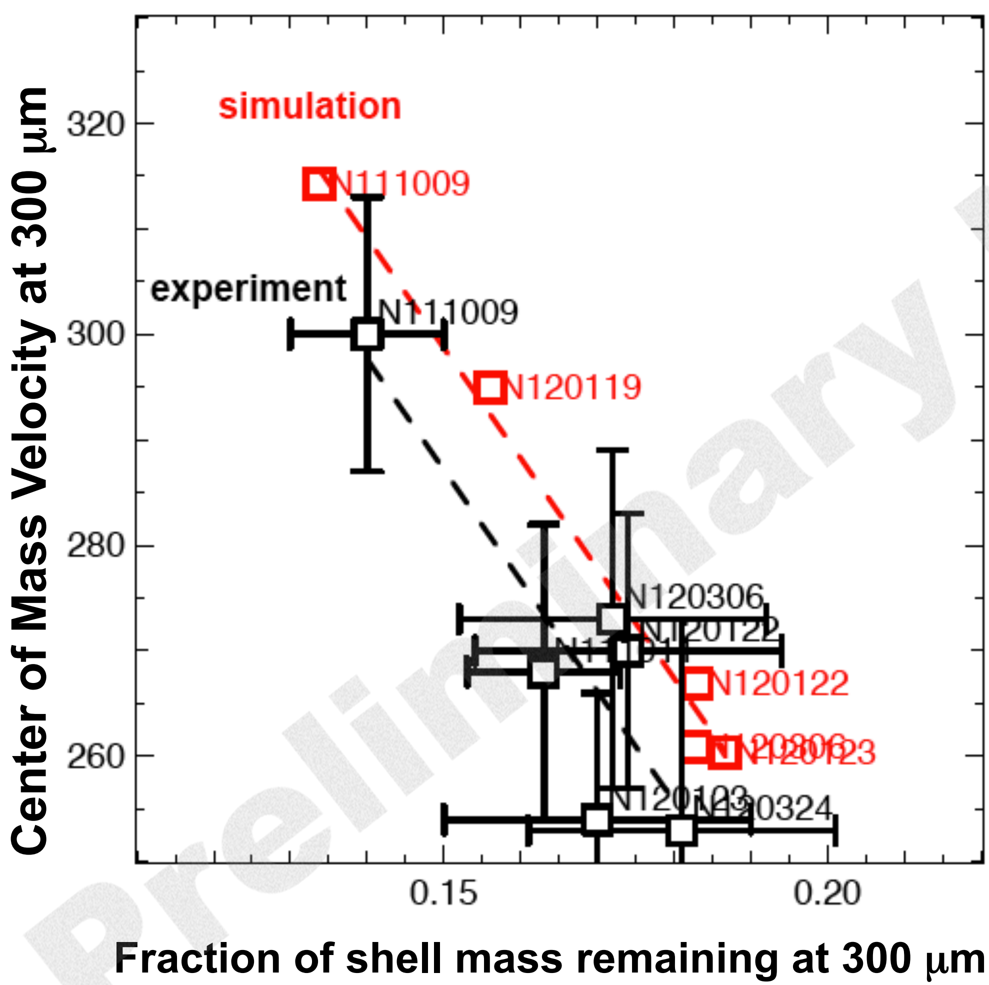
CH Ablation driven implosions follow a rocket curve which allows us to explore mix versus velocity

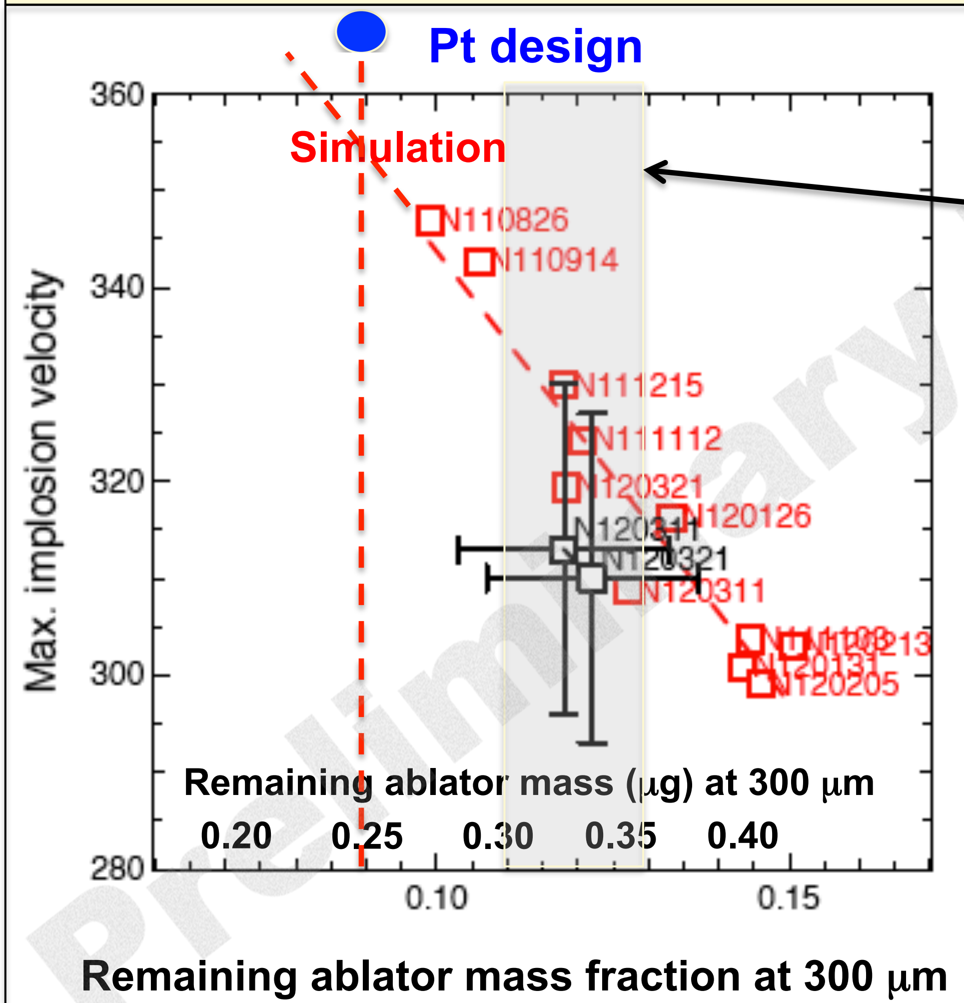
Peak center of mass Fuel Velocity vs Ablator Mass Remaining in convergent ablator symcaps



- Capsule drive in the simulations are adjusted to match the keyhole shock timing data and the convergent ablator radius versus time
- Data is estimated to have 1% less mass remaining at a given velocity than the 1D simulations
- We are exploring whether hydro instability in the imploding shell contributes to this difference

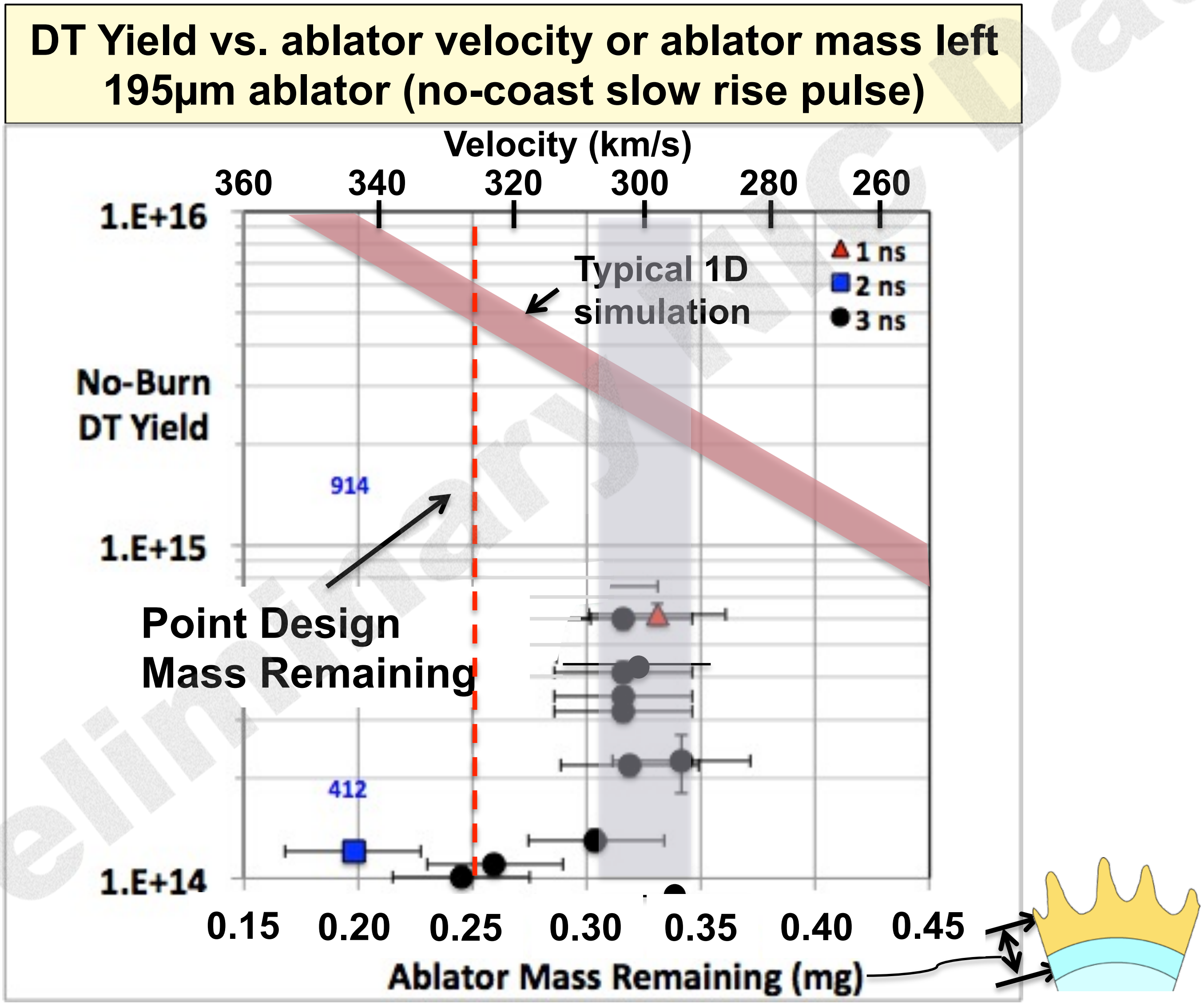
Calculations of the convergent ablator experiments are used to assess the velocity and remaining mass in cryo layered implosions

Peak Fuel Velocity vs Ablator Mass Remaining for cryo-layered implosions



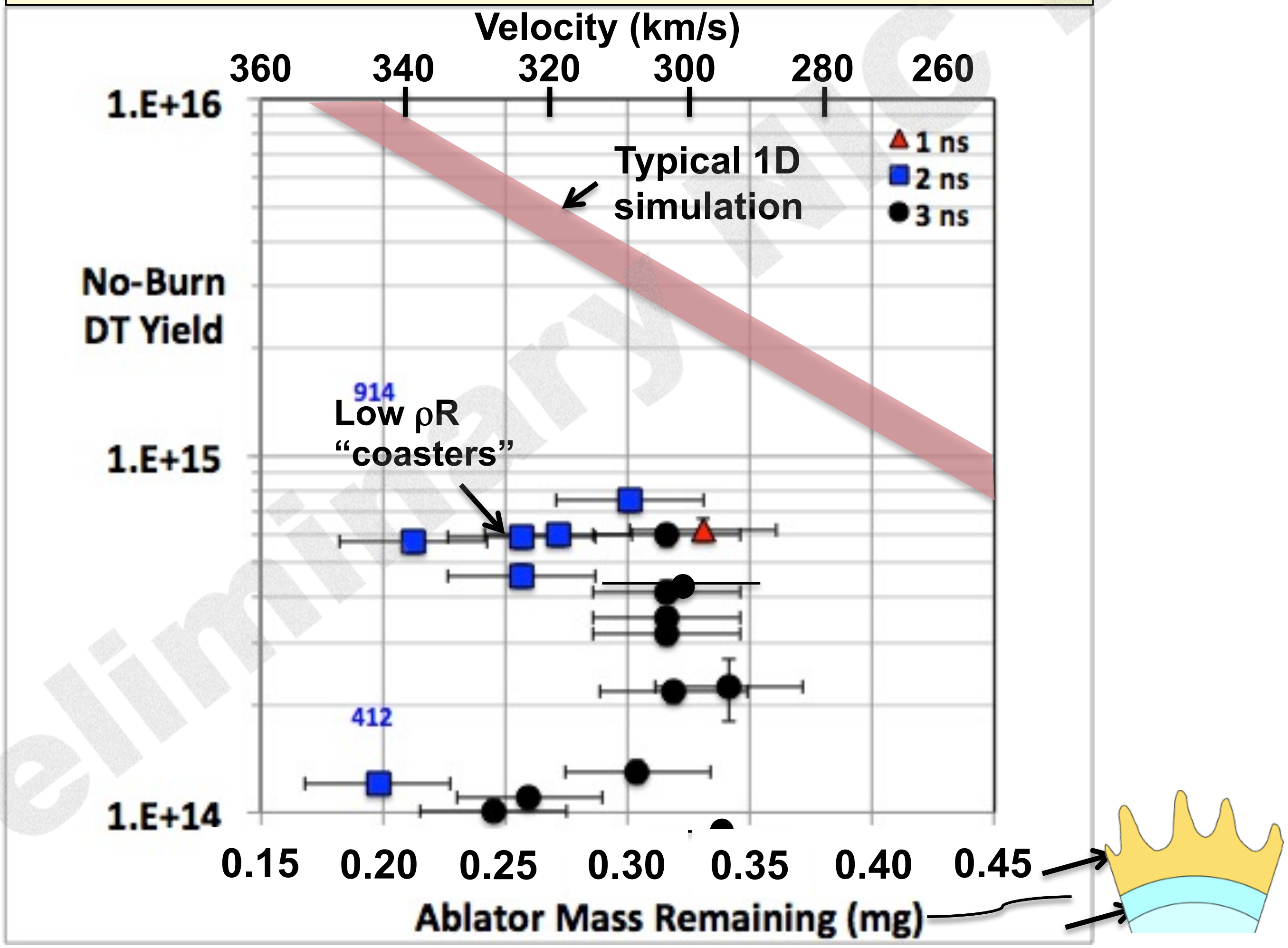
- We find a mix performance boundary at 20-40% more mass remaining than that calculated for the point design

We find a fairly sharp performance boundary with ~20-40% more ablator mass remaining than that for the point design

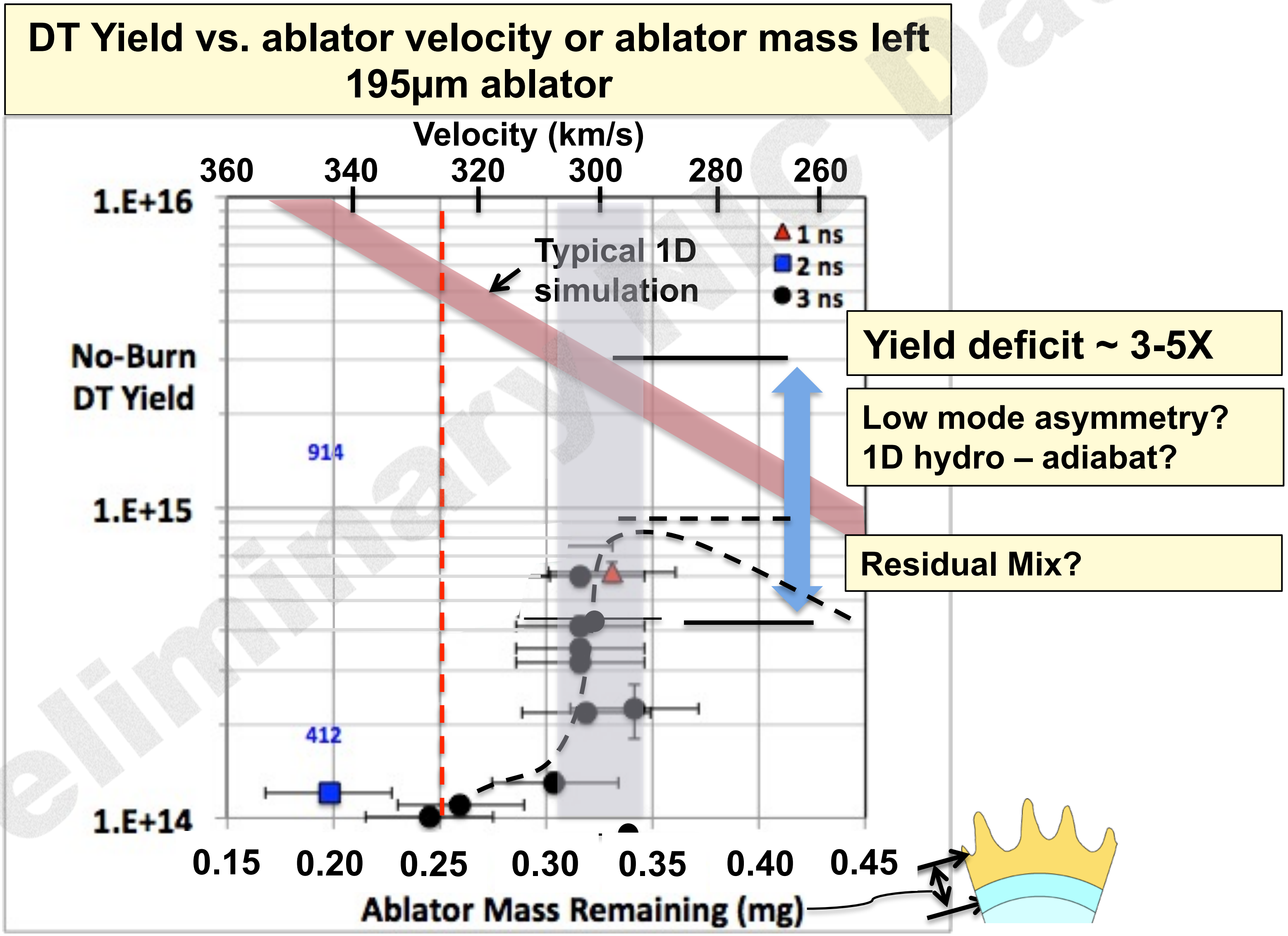


Implosions with coasting decompress and appear to have a mix performance threshold at lower mass remaining, but get much lower ρR and a lower fraction of 1D yield

DT Yield vs. ablator velocity or ablator mass left
195μm ablator

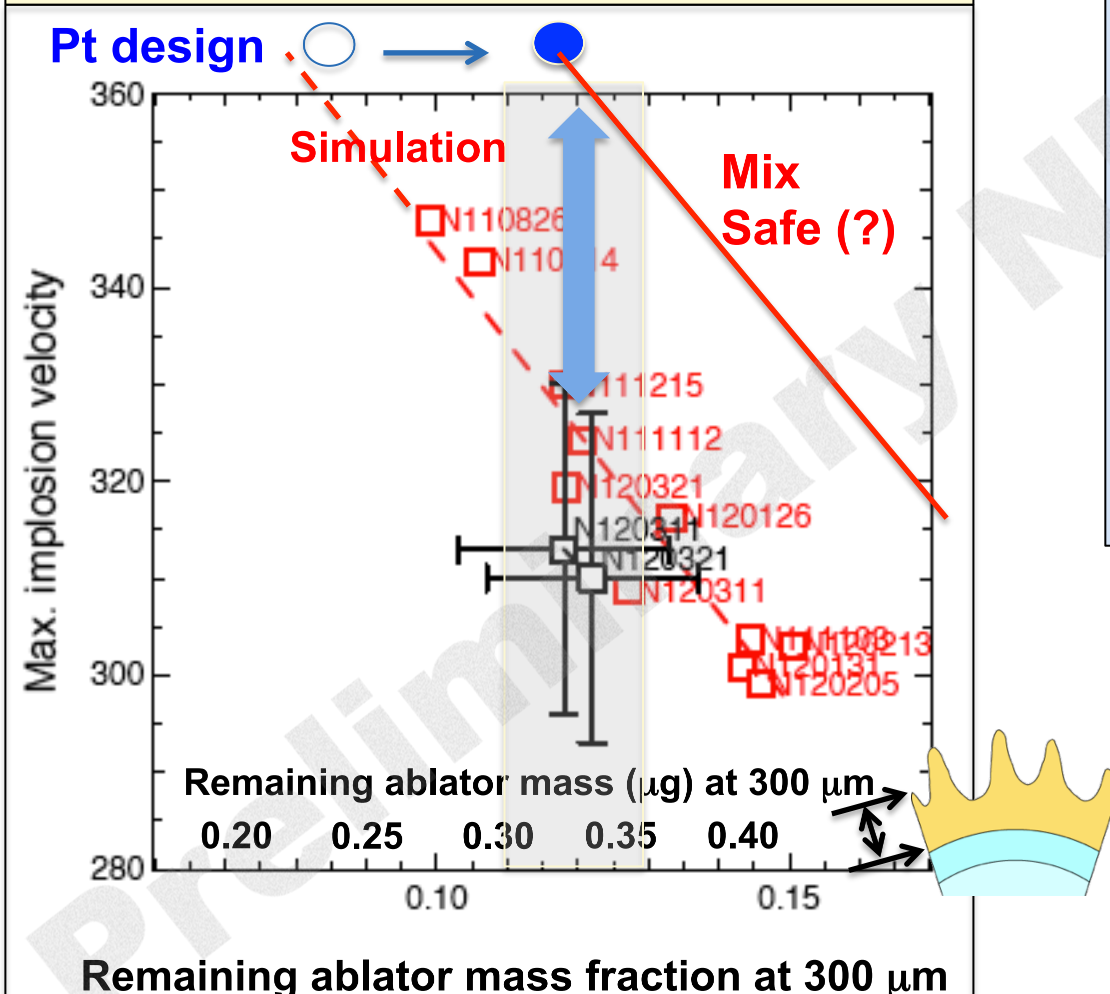


Increasing the yield a factor of 3-5 yield at the current velocity is a key element of upcoming experiments



To get to the point design velocity, we need to increase velocity while keeping mass remaining “mix safe”

Peak Fuel Velocity vs Ablator Mass Remaining for cryo-layered implosions



$V_{imp} \sim \sqrt{(ZTr/A)}\ln(M_0/M_r)$

Per Rocket Model:
+20% V_{imp}, same M_r:

+20-30% M_0 (+40 to 60 μm)
+10% Tr (290 to 320 eV)

Same DU hohlraum:
+40-50% Peak Power (320 to 450-500 TW)
+0.4-0.5 MJ (1.9 to 2 MJ)

- Improve capsules to reduce seeds
- Measure RT and RM growth to identify ways to reduce growth
- Reduce low mode asymmetry to minimize “thin spots” in fuel

Summary of Ignition Campaign Status

- We are one year into the campaign to carry out precision optimization of ignition scale implosions

- We have achieved hohlraum temperatures in excess of the 300 eV ignition goal with hot spot symmetry and shock timing near ignition specs

- Slower rise to peak power and longer "no-coast" pulses result in lower hot spot adiabat and main fuel ρr at about 85% of the ignition goal

- Nuclear data indicates that long wavelength variation in the main fuel density may be contributing to performance degradation

- Mix performance boundary with more mass remaining than the point design will require thicker shells (+20-30%) to reach ignition velocity without mix

These areas plus the temporal history of the main pulse will be the focus of ignition experiments moving forward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